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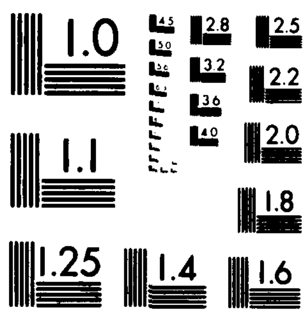

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FINAL REPORT
AI&DS TR-1008-1

October 1981

DECISION AIDS DERIVED FROM HARPOON/TOMAHAWK TARGETING CONSIDERATIONS

Ami Arbel
J. Roland Payne
Richard M. Tong

Contract No. N00014-80-C-0813
AI&DS Project No. 1008

Prepared for:

Operational Decision Aids Project
(Codes 431, 434, 437, 455)
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

ADVANCED INFORMATION & DECISION SYSTEMS
Mountain View, CA 94040

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Naval warfare scenarios highlighting decisions sensitive to the use of long-range standoff weaponry (e.g., Tomahawk) were developed from a Naval officer's perspective to characterize a set of Naval task force decisions from a decision theorist's perspective. Decision aiding technology was reviewed and deficiencies noted in the areas of options generation and value assessment. An aiding procedure focussing on these areas was designed, based on an analytic hierarchy process.

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GLOSSARY

AAWC	Anti Air Warfare Commander
ACCAT	Advanced Command and Control Architectural Testbed
ASUWC	Anti Surface Warfare Commander
ASW	Anti Submarine Warfare
ASWC	Anti Submarine Warfare Commander
A-6	Heavy attack aircraft, carrier based
A-7	Attack aircraft, carrier based
BF	Battle Force
BG	Battle Group
BGIGS	Battle Group Inter Gaming System
CCG	Commander Carrier Group
CG	Cruiser
COD	Carrier Onboard Delivery aircraft
COMNAVAIRPAC	Commander, Naval Air Forces, Pacific
COMNAVSURFPAC	Commander, Naval Surface Forces, Pacific
CTF	Commander Task Force
CV	Carrier
CVBG	Carrier Battle Group
CWC	Composite Warfare Commander
CZ	Convergence Zone
DARPA	Defense Advanced Research Projects Agency
DDG	Guided Missle Destroyer
EMCON	Emissions Control
E-2C	Airborne early warning, command and control aircraft, carrier based
EA-6	Electronic Countermeasures Heavy Attack Aircraft, CV based

FEBA	Forward Edge of the Battle Area
FF	Fast Frigate
FLEETEX	Fleet Exercise
F-14	Intercept/Fighter, carrier based
HF	High Frequency
KA-6	Tanker version of A-6
LOI	Letter of Instruction
OCE	Officer Conducting the Exercise
ODA	Operational Decision Aids
ONR	Office of Naval Research
OPAREA	Operations Area
OPORDER	Operations Order
OPPLAN	Operations Plan
OTC	Officer in Tactical Command
P-3	Long Range Maritime Patrol Aircraft, land based
REMBASS	Remotely Monitored Battlefield Area Sensor System
SCTG	Surface Combatant Task Group
SH-3	ASW Helicopter, carrier based
SS	Conventional attack submarine
SSGN	Nuclear submarine with cruise missiles, Orange
SSM	Surface-to-Surface Missile
SSN	Nuclear attack submarine
TAC D&E	Tactical Development and Evaluation
TASM	Tomahawk Anti-Ship Missile
UNREP	Underway Replenisment
URG	Underway Replenishment Group

1. INTRODUCTION

1.1 OBJECTIVES

The study objectives have been to:

1. characterize the decision space at the Task Force Commander level, particularly as impacted by new weapons and new Navy tactical command concepts.

2. identify areas for new decision aid ideas

3. provide designs for a new set of decision and planning aids

1.2 BACKGROUND AND MOTIVATION

Three efforts, among many others, were undertaken at the beginning of the Office of Naval Research's Operational Decision Aids (ODA) Program:

1. the characterization of the Naval task force decision environment (Ref. 1),

2. the development of the ONRODA warfare scenario for use in development and evaluation of decision aids (Ref. 2), and

3. a survey of potential decision aid technologies (Ref. 3).

Several decision aiding techniques were subsequently delineated, developed, and evaluated.

However, since the beginning of the ODA program (1) critical aspects of the future Naval task force decision environment are changing, and (2) new technology capability has become available. Hence it is appropriate to update the characterization of the decision space and again identify and develop new techniques for aiding Naval task force decision processes. The following two subsections indicate the nature of these changes, which have motivated analyzing the operational decision aids problem area again.

1.2.1 Naval Task Force Decision Environment Changes

Two important new factors have been introduced into the Naval Task Force that significantly impact the decision environment: long range surface strike weapons, and the Composite Warfare Commander concept. There have also been advances in computer capabilities and decision and planning aids since then. The U.S. Navy has implemented the Harpoon weapon system on many naval combatants and is currently providing an inventory for the P-3 patrol squadrons. The Harpoon provides the surface and submarine combatants their first over-the-horizon surface strike capability. The airborne Harpoon capability further extends the range from friendly surface combatants at which targets can be attacked. The Tomahawk cruise missiles (both the Tomahawk anti-ship missile (TASM) and the Tomahawk land attack missile are currently under test and evaluation) are expected to significantly increase the surface strike range for U. S. Navy surface ships and submarines. They will probably also eventually be used by Navy attack aircraft. These new long range offensive weapon systems are likely to profoundly affect task force decisions, planning, and operations.

Potential U.S. Navy adversaries are also increasing their capabilities with cruise missiles.

Limited numbers of these expensive long range weapon systems are being installed in naval platforms that will also retain their earlier capabilities to perform multiple missions such as anti-air warfare (AAW), anti-submarine warfare (ASW) and anti-surface warfare (ASUW). Hence many more "reasonable" options are becoming available to the decision makers. To use these long range weapons most effectively, information from many sensor/intelligence sources, not all under the control of the platform firing the missile or even the local tactical commanders, will be needed. Duration and timing of maneuvers to use the missiles may be very important decision factors. The question of who the decision maker should be, may be focused on again.

The task force commander's staff is likely to have the same organization as before, see Figure 1.1 (Ref. 4). These officers are all involved in task force level decisions and planning. During the execution phase the Composite

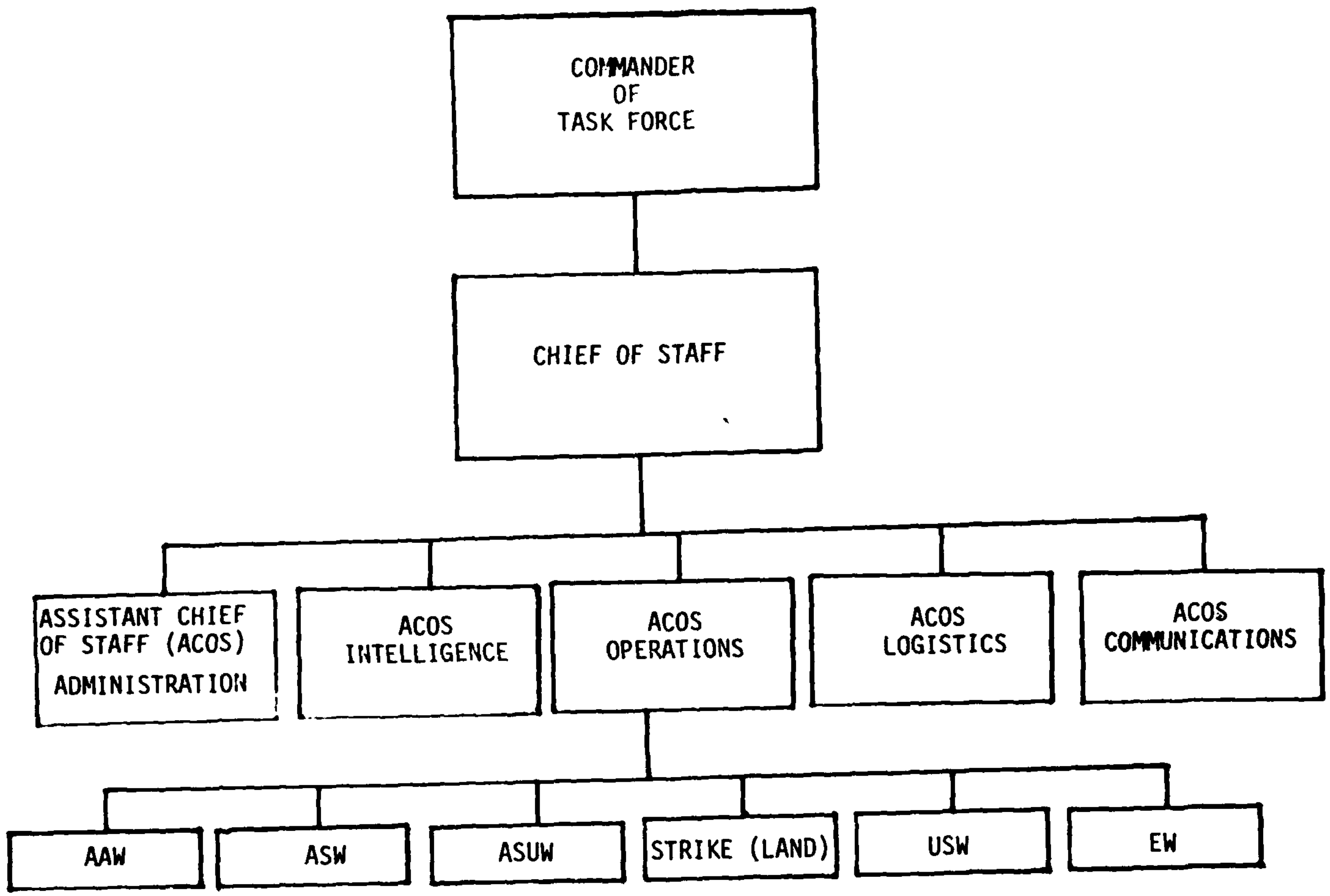

Figure 1.1 Staff Organization

Warfare Commander (CWC) concept is likely to be employed (Ref. 5)[1]. The CWC is likely to be the Commander of the Task Force (CTF), but the subordinate commanders for defense of the task force (AAWC, ASUWC, ASWC) are likely not members of his staff, but other senior officers in the task force such as Commodores or Commanding Officers. The CTF staff members will be the CWC watch standers during operations.

Preliminary to the at-sea execution phase, the CTF and his staff are the personnel primarily responsible for decision making, planning, and writing the OPORDER and directives. The subordinate warfare commanders (i.e., AAWC, ASWC, and ASUWC) are also likely to be involved during this planning phase, and will become primary decision makers when the plan is executed. During the planning phase all the commanders and staffs work variously alone and in groups as their other ongoing duties and individual desires permit.

The organizations indicated above constitute a hierarchy, with both lateral and vertical dimensions of decision makers, planners, and controllers, Each member must work at times independently, and at times in direct coordination with others, but with an expectation that a selected course of action might be negated by the CWC soon after its execution commences. Thus it appears that each expert/member should pursue decision making, planning and control in his own area of expertise with a knowledge of the others' perspectives and the interaction effects of other warfare areas with his own. In short, an understanding of a set of measures of effectiveness (MOEs) and associated values, which maps onto the organizational and functional hierarchy, is desired.

1.2.2 Technology Changes

Computer science advances include the implementation of increased communications, storage, processing, and display capabilities. Artificial intelligence techniques are being applied to tactical military problems. In

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[1]The Chief of Naval Operations recently endorsed this concept for Navy wide use. The Reference 5 material is currently being upgraded to a Naval Warfare Publication.

the operations research area increased capabilities to combine process models and optimization have developed and been applied to planning tasks (e.g., route planning for aircraft and cruise missiles (Ref. 6)). Multi-attribute utility theory has continued to develop. The implementation of some interactive decision tree programs has occurred (Ref. 7,8), and continues development. The Analytic Hierarchy Process (Ref. 9) has been applied to many types of complex non-military decision problems. Research is being conducted on distributed sensor networks and distributed decision making in a hierarchical military environment.

1.3 STUDY APPROACH

The intent of this study has been to characterize the decision space and to delineate and design a set of aids, using the above types of advanced technologies, that will be useful in the near future Navy tactical decision environment in training and "war" situations.

The study effort was comprised of an investigation of the decision environment, primarily through the construction of scenarios as examples; a review of pertinent decision aiding technologies, particularly in the areas of decision analysis, psychology, computer science (primarily artificial intelligence), and operations research; and the selection and design of a set of aids. Most of the contract effort was devoted to the last task.

Investigations of the decision environment included discussions with staff officers and analysts for READIEX 4-80, READIEX 5-81, and FLEETEX 1-8, PME-108, (now PME-120), Tactical Training Group Pacific, Battle Group Inter Gaming System (BGIGS), Advanced Command and Control Architectural Testbed (ACCAT), and many Tactical Development and Evaluation (TAC D&E) activities concerned with the employment of Harpoon. Little was found in the way of scenarios that focused on decisions concerning the tactical employment of Harpoon or Tomahawk at long ranges. Based on the insights learned, fictional scenarios were developed for this study and are presented in Section 2. These scenarios do not at all reflect any "Navy blessed" scenarios, none of which could be identified.

The scenarios were developed from a Naval officer's perspective to provide a vehicle for identifying specific insights into the nature of the decision space, from a decision analyst's perspective. They also provided specific situations to analyze while defining and developing a potential decision aid (e.g., the Hierarchical Priority Assessment explained in Section 5).

Concurrently a review was made of the techniques and aids being developed within the ONR ODA program, the ACCAT program, the DARPA Distributed Sensor Network program, the Artificial Intelligence (AI) efforts (particularly in the area of hypothesis generation and evaluation), the decision theory area and the psychology area. Computer programs of some of the developmental techniques were obtained and their potential explored by applying them to mini-scenario decision situations. The sponsor is already well aware of most of the techniques being developed so no attempt is made in this report to present a comprehensive summary of them. However an overview of technologies pertinent to the generation of options (particularly important tasks in the long range weapons decision context) and to value judgements is presented in section 3, with cognitive biases and styles in decision making being stressed.

Examining the reviewed technologies for application in the Naval task force decision space developed in the first task led to the judgmental evaluation that there is a need for

1. procedural aids to help generate a good set of reasonable options to which decision analysis procedures can then be applied, and
2. general aids for decision making in a hierarchical organization, particularly for attaining value/utility assessments.

We also concluded that not sufficient research effort is being conducted in these areas.

We examined several technologies and techniques, with the goal of defining/designing decision aids that address one or both of the two above areas of deficiency and that would augment the set of aids already being developed in the ONR ODA program. We selected the Analytic Hierarchy Process,

which has been applied to several non-military decisions, as the basis for defining and initiating the development of decision aids that would be of value to the decision makers, in both the above areas. The basic elements of such decision aids are discussed in Sections 4 and 5.

2. LONG RANGE WEAPON SCENARIOS AND ASSOCIATED DECISION FACTORS

2.1 PURPOSE

The following scenarios are presented to indicate and describe examples of specific factors and their relationships that might be considerations in some naval task force decision processes. Decision situations are highlighted that are concerned with the potential tactical employment of long range surface attack missiles, such as Harpoon, Tomahawk, and extended range follow-ons to these systems.

The long range weapon systems significantly impact the current tactical decision process because they provide many more tactical options, they have the potential for being used relatively quickly in wide areas of the ocean, they can/should use information from many sensor systems (indigenous and exogenous to the task force with the weapons), and they may focus more effort on considering low probability but high value or high risk events.

Two scenarios are presented in the next two sections. The first is a fictional scenario of "real world" naval operations. An important goal in the development of any potential decision aid is for the aid to increase the decision making effectiveness of officers in such situations.

The second is a fictional scenario of training operations, such as in a FLEETEX. It is in these operations that Admirals and their staffs have their first opportunities to practice making tactical decisions that are actually implemented. It is also in this environment that new aids would be evaluated, and the officers would become proficient in their use, before introduction and use in the "real world" naval operations.

2.2 WAR SCENARIO

2.2.1 Missions, Objectives

There is a two week old, non-nuclear land war between Orange and Grey.

Blue is supporting Grey with land forces, shipping war supplies via convoy, and providing air strikes ashore from a two carrier battle force. Orange and her allies have not yet challenged Blue's naval forces, either with naval units or land-based forces.

The Blue Battle Force's mission is to support the land war with airstrikes and to maintain control of the sea out to 800 NM. Operational objectives under this continuing mission are:

- Provide airstrikes ashore daily
- Keep the sea-lines of communication (SLOC) open
- Provide convoy protection in the terminal area
- Ensure the survival of the Battle Force.

The Orange alliance is most interested in the land war with the intent of gaining control of large regions of Grey. Orange's objectives with regard to the sea forces are:

- Prevent naval power projection ashore
- Prevent resupply to Grey/Blue land forces via the sea

2.2.2 Background

Tension between Orange and Grey had been high for several months before Orange attacked and drove into Grey. During these months Blue provided Grey with land combat equipment, including Improved Hawk Air Defense Batteries, Cobra helicopters equipped with TOW anti-tank missiles, M-60 tanks, Armored Personnel Carriers, and remotely monitored battlefield area sensor systems (REMBASS). Blue also provided a large cadre of training and maintenance personnel for these advanced systems to the Grey troops. Additionally Blue had one mechanized infantry division stationed in Grey.

Orange had conducted war games on its side of the border twice within the last 15 months. Each time they stock piled more war materials near the border and left more troops stationed there. They were in the third day of what at first appeared to be another large scale training maneuver when they turned

and made a major thrust into Grey some 200 NM from the coast.

Grey/Blue resistance was tougher than expected and the thrust was checked after a penetration of approximately 125 miles. Orange forces did not reach and control the Grey coast. However, Orange reserve forces have been reinforcing and another major offensive is expected within the next four days.

Blue had positioned its two carrier Battle Forces near Grey a few months before the attack, to show the flag and hopefully deter aggression. Heavy air strikes from these two carriers were credited with helping to slow the Orange thrust after their initial incursion into Grey. Immediately after the Orange attack Blue decided to send large quantities of war materials and additional troops. No need for an amphibious landing was forecast, but the Orange side might use submarines, surface forces and long range air against the supply ships. Hence a few large, fast container ships were sent (individually) and a large convoy followed.

The Blue Battle Force continued to operate in accordance with the general OPORDER that it had been using, with message modifications when required. In particular the schedule of events has been changing frequently.

The enemy had sent three submarines toward the area. A major task force of surface combatants was approaching the general area from distant ports. Orange allies also can send long range bombers equipped with anti-ship cruise missiles to operate from Orange airfields.

2.2.3 Current Naval Situation

No naval engagements have occurred to date, but Orange surface forces with long range surface-to-surface missiles are closing the Blue Battle Force. Orange submarines are already somewhere in the Blue BF operating area. The following two sub-sections present the composition and positions of both sides. Blue does not know all Orange force compositions and positions accurately. Figure 2.1 depicts current actual forces.

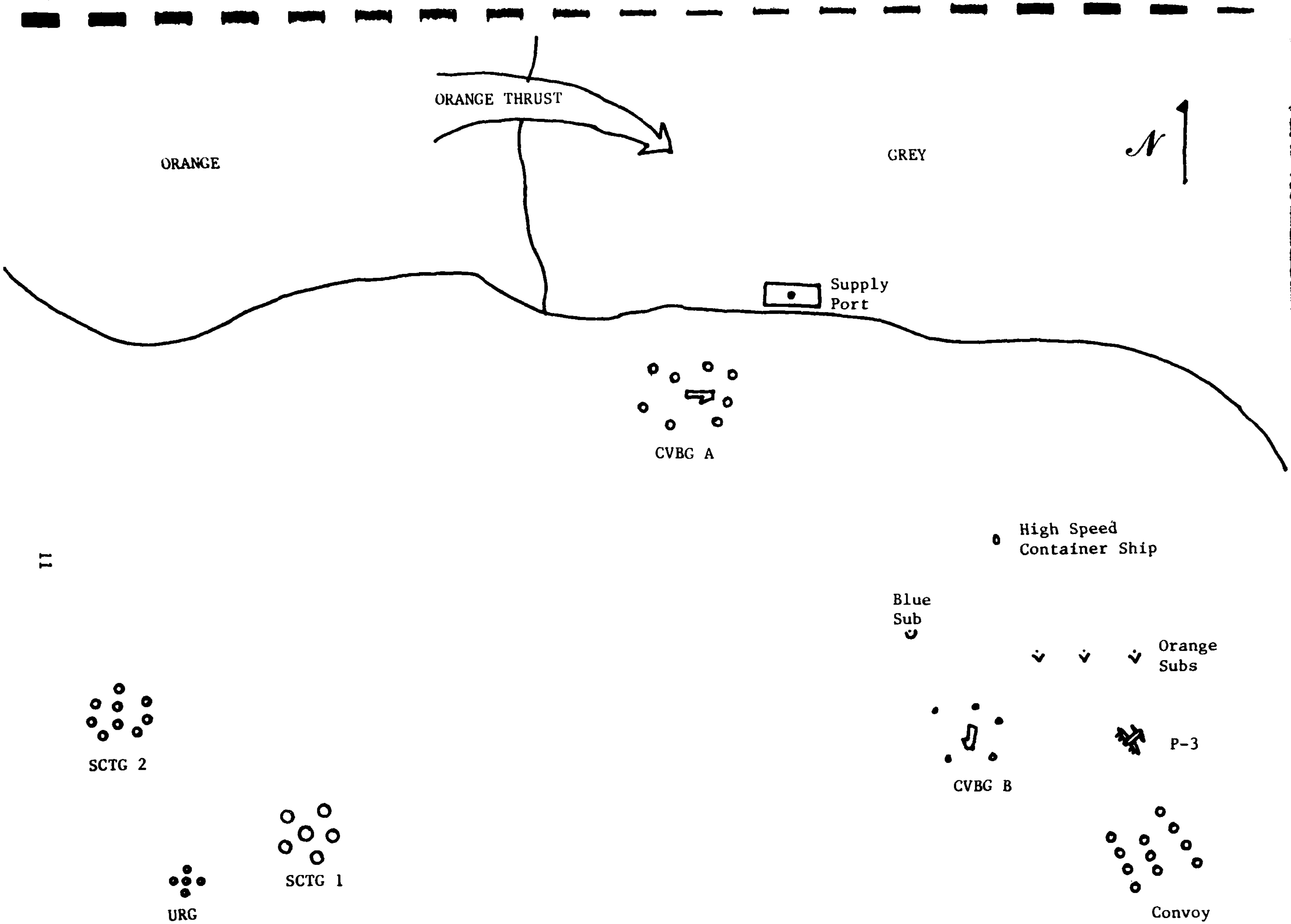

Figure 2.1 Current Naval Forces

2.2.3.1 Blue Naval Forces

The Blue Battle Force is organized into two carrier battle groups, CVBG-A and CVBG-B. CVBG-A is 100 NM from the coast conducting airstrikes ashore. CVBG-B is 500 NM out conducting an ASW search and preparing for convoy protection. Table 2.1 indicates the Battle Groups' compositions. There is one Blue Tomahawk equipped submarine in direct support of CVBG-B. There is one Harpoon equipped P-3 aircraft on station conducting an ASW search in front of the convoy. (The P-3 on station can be augmented by another P-3 on a surge basis, for a maximum of two P-3s on station for two four-hour periods; then only one P-3 can be anticipated on station. The P-3s have a radius of action of 1000 NM from CVBG-A, with an on-station time of two hours at the maximum radius of action.)

The Blue Battle Force has been operating with no EMCON restrictions.

The Blue Battle Force is supported by Fleet and National sensor systems. Passages into the operating area are covered with long range sonar systems, but not the area itself. The HFDF system has some capability, but generally poor accuracy in the area. Satellite systems are tasked to provide tactical information.

The Fleet Commander is ashore, thousands of miles away. Satellite and HF communications have been reliable on all nets. The Fleet Ocean Surveillance Information Center for all source information of concern in the operating area is at Fleet headquarters.

A convoy of 11 supply ships is 600 NM from the supply port in Grey, with a speed of advance of 12 knots.

The command structure within the Battle Force is in accordance with the Composite Warfare Commander concept (See Reference 3). Each CVBG is organized in that manner with the OTC of the combined force embarked in CV-A and retaining the role of CWC for CVBG-A. The AAWC for each CVGB is embarked in a CG while the ASUWC and ASWC are both embarked in the carrier, for each CVBG. The CWC for CVBG-B is embarked in CV-B. The SSN and P-3 are currently both under the control of the ASWC in CVBG-B.

Table 2.1 Blue Battle Group Compositions

CVBG A	CVBG B
CV-1	CV-2
24 A-6, EA-6, KA-6 (Harpoon Capable)	12 A-6, EA-6, KA-6 (Harpoon Capable)
24 A-7	24 A-7
24 F-14	24 F-14
4 E-2C	4 E-2C
4 SH-3	12 S-3A
1 COD	8 SH-3
	1 COD
2 CG	1 CG
3 DDG (Two Equipped with Tomahawk)	2 DDG (One with Tomahawk)
3 FF (Two Equipped with Harpoon)	2 FF (One with Harpoon)
	1 SSN (Equipped with Tomahawk)
*	*

* P-3 (Harpoon equipped) can be maintained in direct support to the Battle Force, in 4 hour on-station intervals. Surge capability to two P-3s for two consecutive 4 hour periods.

2.2.3.2 Orange Naval Forces

The Orange Naval Force is composed of two Surface Combatant Task Groups (SCTG), three submarines and an underway replenishment group (URG). Table 2.2 indicates their compositions. SCTG-1 is 600 NM west of CVBG-B, with SCTG-2 150 NM northwest of SCTG-1. The URG is 75 NM west of SCTG-1. They are steaming on a base course of 060 with an SOA of 15 knots. The three submarines have stationed themselves on the expected Blue convoy route.

The mission of the Orange forces is to degrade the strike effectiveness of the Blue Battle Force and to prevent Blue supply by sea. Specific objectives are to make coordinated long range missile attacks on the Blue carriers and torpedo attacks on the convoy.

All Orange forces have operated under strict EMCON to this time.

2.2.3.3 Environment

The weather has been clear and hot in the Blue operating area for several days. However a severe squall line and low pressure trough is approaching from the west at 17 knots. It currently extends north and south, located between Orange SCTG-1 and SCTG-2.

The acoustics in the Blue operating area and along the convoy route are poor, with convergence zone (CZ) detection of quiet submarines unlikely. However, noisy surface traffic can probably be detected in the second CZ.

Radar ducting is present, allowing surface detections out 40 to 50 NM. However, within 150 NM of the squall line this pattern is broken, permitting radar detection only within normal line-of-sight.

Sea state 1-2 prevails throughout most of the area. Within 50 NM of the low pressure trough the seas begin to roughen, building to sea state 4 in the squall line. Sea state 3 exists for approximately 150 NM behind the squall.

2.2.4 Decision Characteristics and Considerations

The above brief scenario description did not explicitly mention any decisions that were made in arriving at the current situation. Clearly many

Table 2.2 Orange Naval Force Composition

SCTG-1	SCTG-2	URG	SUBMARINES
1 Cruiser (Long-Range SSM) 2 Destroyers 2 Fast Frigates	2 Cruisers (Long-Range SSM) 3 Destroyers 4 Fast Frigates	3 Supply Ships 2 Fast Frigates	2 SSGN (1 Long-Range SSM 1 Short-Range SSM) 1 SS
Aircraft: 10 Backfire and 20 Badger aircraft equipped with air-to-surface missiles arrived at an interior Orange airbase yesterday. Their radius of action extends 700 NM to sea. 2 Bear-D aircraft are also there.			

decisions were needed and made, and perhaps a major decision should now be made to successfully continue operations. This section calls attention to several decision factors that were not present in tactical operations a few years ago, e.g., refer to the decision spaces and scenario described in references 1 and 2. (The decision considerations cited then are still valid now.)

- The long range weapons on the submarine, surface ships, A-6, and P-3 provide additional capability to those platforms, while detracting little from the capabilities they previously had (and still have)

- The submarine and both types of aircraft, provided they can attain adequate targeting information, can make attacks with little risk to themselves from immediate counter attack.

- The Blue surface ships with Tomahawk (or Harpoon) may be at risk since the enemy has SSMs with approximately the same range on some of their units. But the side that first targets the opposing surface units is likely to have a significant time advantage over the other side (as compared to reaction time to attacks by short range weapons).

- Coordinated attacks with manned attack aircraft following the long range missiles may provide for more precise and devastating use of current war-at-sea weapons.

- Targets can be attacked in large areas of the ocean (as compared to now: a few hundred miles around a CV or a few tens of miles around surface combatants).

- Hit and run attrition tactics can be used. Dominant local control of the ocean is not required for successful attacks.

- There are more "reasonable" options to consider.

- There is less local control of sensor and information systems required to effectively employ the long range weapons. Systems exogenous to the Battle Force are more critical to the tactical engagement.

- There are more potential sources of tactically useful information.

- There is likely to be more uncertainty in the information (e.g., less precise measurements by long distance sensors, less definitive classification data, more redundant and sometimes conflicting data, data acquired over time with reports arriving out of order).

- Who should bear the responsibility of actually firing long range weapons is more questionable (i.e., should it be the commander with the most complete, or best, information, the commander whose platforms carry the missiles, or some combination?).

In the scenario described the mission objective of Battle Force survival rises in priority with the increasing naval and air threat; the objective of SLOC and convoy protection also rises as the convoy enters the suspected enemy submarine area, and the land combat support objective intensifies as enemy reinforcements arrive in the front lines.

2.2.5 Alternative Options

There are several options for current consideration that involve alternative uses of the multi mission capable platforms carrying the long range weapons. They involve finding the right amount and type of resource, and the right timing for engaging each enemy resource: URG, SCTG-1, SCTG-2, submarines, long range air, and land combat units. Refinements to the options should consider such things as which specific ships within the URG and SCTGs should be primary targets. Six "reasonable" example options to consider, which move progressively from current operations toward emphasizing the destruction of enemy surface forces, are given in Table 2.3.

Other "reasonable" options would consider alternative resource assignments for more effectively countering the submarine threat, or for defeating the potential air threat.

There is a continuing need to counter all types of threat. So the amount of time a potential operation would take a resource to accomplish, and then return to a longer term warfare task, is an important characteristic of each alternative option. Long range weapon actions against surface forces can be relatively short as compared to ASW search, maneuvering for short-range weapons engagement, etc. For example: a P-3 coming on station for ASW might be diverted a few hundred miles to attack an URG or harass an SCTG with Harpoons with only a subsequent loss of an hour or two of on-station ASW time. What is the probability the P-3 would have denied an enemy submarine the opportunity of attacking during that time?

The added capability of long range weapons provides a large degree of flexibility to the decision space. So much so, that a reasonable question is,

Table 2.3 Example Options

Option	Blue Resource	Assignment
1.	CVBG-A	Continue airstrikes, maintain air defense posture
	CVBG-B	Continue closing convoy, ASW
	SSN	Continue ASW
	P-3	Continue ASW for convoy
2.	CVBG-A	Same
	CVBG-B	Same
	SSN	Same
	P-3	Reassign to ASUW strike on URG or SCTG-1
3.	CVBG-A	Same
	CVBG-B	Detach SAG (with Tomahawk) for SCTG-1
	SSN	Same
	P-3	Same as 2
4.	CVBG-A	Detach SAG (with 2 Tomahawk ships) for SCTG-2
	CVBG-B	Same as 3
	SSN	Same
	P-3	Same
5.	CVBG-A	Same as 4, cease airstrikes, move toward convoy
	CVBG-B	Same as 3, send flight of A-6 (Harpoon) with P-3
	SSN	Proceed with SAG for SCTG-2
	P-3	Same as 2, call for surge P-3 to join
6.	CVBG-A	Cease airstrike, maneuver for war-at-sea strikes
	CVBG-B	Same as 5
	SSN	Same as 5
	P-3	Same as 5

"What is a reasonable set of 'reasonable' options to evaluate in a pragmatic operational decision process?" How much time, ingenuity, and effort should be used in identifying the set of options? How much time and effort is available for evaluating the selected alternatives?

2.3 TRAINING SCENARIO

2.3.1 Overview of a FLEETEX

A major training exercise such as a FLEETEX comprises an at-sea period of approximately two weeks, the culmination of months of decisions, planning, scheduling, and preparatory exercises. It is followed by a Hot Washup (a quick assessment of significant events and lessons learned), a few weeks of analysis, and some reports. It is then to a large extent forgotten--or is it? Each participant gained valuable experience, learning to accomplish procedures more expertly, and finding out pitfalls to avoid in the future. The lessons learned and analysis reports can be used to improve future training and provide guidance in the development of improved or new systems. The LOI, OPPLAN, and OPORDER might even be used as a template for planning the next FLEETEX.

The FLEETEX starts to become formal after a Quarterly Scheduling Meeting in which organizations, ships, and air wings are identified. The Numbered Fleet Commander (Commander Second Fleet or Commander Third Fleet) writes a Letter of Instruction (LOI) designating the Officer Conducting the Exercise (OCE), who is likely to be the Commander of a Carrier Group (CCG), scheduled to deploy soon after the FLEETEX, the resources assigned, the mission (e.g., training and tactics evaluation), and the dates (on the order of six months later). The OCE and his staff then develop an OPPLAN, identify the subordinate warfare commanders, and work up the OPORDER. This months-long effort takes place while the personnel, ships and aircraft units are still attached to their administrative commands (e.g., COMNAVSURFPAC, COMNAVAIRPAC) and are undergoing individual training and participating in other exercises (e.g., COMPUTEX, READIEX). The ships, aircraft, and training facilities are scattered over a large geographic area during this period of time when the OCE and his staff are making decisions, plans, and schedules for the FLEETEX.

The OPORDER is promulgated on the order of one to two months before the FLEETEX at-sea activities. Numerous modifications are then promulgated by message.

A typical FLEETEX OPORDER might contain some five or six phases. For example, the phases could be

1. Multi Weapon System Trainer--a Training Command trainer that ship and aircraft crews use to simulate tactics in a controlled warfare situation, a few days before going to sea.

2. Opposed Sortie--The task force attempts to leave port without the carrier(s) being attacked by opposing submarines.

3. Individual Ship Exercises and Specialized Warfare--Underway replenishment (UNREP), AAW, ASUW, and ASW exercises are sequentially practiced. Air wing carrier qualifications are updated.

4. Practice and Live Weapon Firing on a Missile Range--Surface and Air Targets are used, safety and range telemetry requirements may severely constrain tactics.

5. Scenario--Blue and Orange forces conduct a war-at-sea in the assigned operating area over several days. Additionally Blue may conduct airstrikes ashore.

6. Transit--Return to home ports.

The scenario phase above is the most complex and exercises the forces in an integrated manner. As indicated in the above paragraphs the decision making concerning major use of all assigned resources for this phase occurs over the months preceding the actual execution phase. The decision makers are busy with a myriad of other tasks during this time, but with proper aids there may be enough time to perform thorough decision processes. There will still be an abundance of decisions to appropriately make during the scenario phase.

2.3.2 <u>FLEETEX Scenario</u>

The exercise forces are split into Blue and Orange as indicated in Table 2.4. Intelligence and surveillance resources ashore support both Blue and Orange.

Table 2.4 Force Compositions

Blue	Orange
CV 12 A-6, EA-6, KA-6 (Harpoon Capable) 24 A-7 24 F-14 4 E-2C 12 S-2A 8 SH-3 1 COD 2 CG 2 DDG (One with Tomahawk) 2 FF (Both with HARPOON) 1 SSN (with HARPOON) 2 Lamps 9 P-3 (with HARPOON)--can have at most three 5 hour on-station periods per day	1 CG (with Tomahawk range missiles) 3 DDG (Two with HARPOON range missiles) 2 FF (One with HARPOON range missiles) 3 Helicopters 3 SSGN (Two with Tomahawk range missiles) Land Based Air 9 P-3 (Simulate Bear-D) Can have at most three 4 hour on station periods per day) 12 F-14 (Simulate Backfires) 24 A-7 (Simulate Badgers)

War has been declared, and hostilities have been going on between Blue and Orange land forces for several days. Nevertheless, for the exercise, all targets r t be positively identified before attack (to preclude attacking airliners, merchant ships, or other non-participants that may pass through the operating area).

Blue's Battle Group mission is to destroy the Orange naval force and to conduct airstrikes on coastal targets and on targets approximately 100 NM inland.

Orange's mission is to prevent the Blue BG from making strikes ashore.

Both naval forces are constrained to remain in the designated exercise operating area, a roughly rectangular area, 300 NM by 400 NM, adjacent to the Southern California and Baja California shoreline. Flights inland cannot overfly Baja California. Each side must conduct underway replenishment. The supply ships can not be attacked en route to the combatants, but attacks can be made while an underway replenishment (UNREP) is being conducted.

This FLEETEX is the first time that A-6s have had a HARPOON capability. It is also the first time to introduce the Tomahawk anti-ship missile (TASM) into a FLEETEX. (Note that when the F-14 was first introduced into the fleet it was used much like an F-4 despite its longer range radar and missile; also the average range at which the HARPOON SSM was fired was less than the firing ship's radar range for many FLEETEXs after the HARPOON's introduction into the fleet.)

The current situation is that the Blue and Orange units have just separated into two distinct Battle Groups preparatory to COMEX for the Scenario Phase. The Scenario Phase does not start for 16 hours. Neither side can actively try to detect the other during this time. Each side is steaming under strict EMCON toward starting positions of their choice; however, Blue is constrained by higher authority to the southwest quadrant of the OPAREA.

There are umpires aboard who will assess damage from attacks on the ships they are riding, and degrade their future capability according to random

number draws entered into applicable casualty tables. Because of the emphasis on training during the FLEETEX any damaged unit will only operate in a degraded mode for a few hours at most before being able to again use its full capability.

The weather is clear, visibility about 20 NM. Acoustic conditions are the normal ones for the Southern California OPAREA. There is no radar ducting present. No change is expected.

2.3.3 Decision Characteristics and Considerations

The factors enumerated in Section 3.2.4 for the War Scenario are valid here also. Additional factors are:

- No matter where the initial opposing force positions are, they are (or nearly are) within long range missile distance--because of the OPAREA constraints.

- Maintenance and supply are manned largely by relatively inexperienced personnel. The aircraft sortie rate may degrade appreciably in the first around-the-clock at-sea operations.

- Establishing communications and initiating known tactics may take considerable time in multi-unit activities--until this coordination has been practiced several times. This problem is greater in connection with developmental tactics.

- The enemy won't stay killed.

- Damage is not evident. Time elapses before damage assessment messages arrive from umpires.

- Classification of "enemy" units is difficult because both sides use the same types.

- Tasking of fleet and national sensor systems may not be as reliable as in a real world war situation.

- The decision makers may appreciate any guidance on how to proceed, rather than searching for the best way to proceed.

2.3.4 Alternative Options

There are many major plans that can be used for the Blue commander's two major objectives: win the "war," and achieve maximum training.

Because of the low inventory of long range missiles, now and expected on the long deployment following the FLEETEX, the OTC feels that training in using the other "normal" type of weapons is very important. But the potential of the long range weapons, if they can be employed correctly, needs exploring and might significantly help "win the war" with considerably less damage to Blue forces. Thus for each major option there are suboptions on how much to emphasize the "new" long range weapon systems.

Reasonable major alternative options to consider are:

1. Position and commence airstrikes ashore as soon as possible. Defend Blue forces when attacked.

2. Actively find and destroy the Orange surface force, then commence airstrikes ashore; continuous ASW and AAW.

3. Remain passive, covertly find Orange surface forces, surprise attack (led by long range missiles), then airstrikes ashore; continuous ASW and AAW.

4. Find and destroy Orange surface and subsurface forces, airstrike enemy bomber airfields, then airstrikes in support of land combat.

3. TECHNOLOGY SURVEY IMPLICATIONS

A cursory survey of the progress in computer hardware and software developments quickly indicated an increased capability to communicate data and use more powerful models in processing the data. However, the fundamental problem of structuring appropriate decision models and evaluating the various decision factors in the context of the specific decision situation and decision makers remains difficult. The initial decision structuring (i.e., identifying the options) and making first estimates of the relative importance of a myriad of pertinent decision factors is currently left mostly to the human decision makers. This, combined with an early recognition of the importance of decision spaces characterized by a large number of options involving potentially high values and large uncertainties, led to concentrating our technology search in the psychological area and to techniques that required significant human interaction. The psychological literature contains many observations and insights that we feel should be recognized, largely as constraints, during the design of decision aids, requiring an extensive interaction with the decision makers. These constraints and insights, from references 10 through 22, are summarized in Appendix A.

Our review of the literature shows that decision scientists have generally ignored the problem of options generation except to mention it in passing as the most creative part of the decision making task. This is somewhat surprising since the ultimate quality of the decision making process depends upon the assumption that the "best" solution is in the original choice set. There has, however, been some analysis of the option generation problem in both the behavioral psychology and computer sciences literature. Within these disciplines it is possible to identify both passive and active option generation strategies. By this we mean that some approaches actively attempt to prompt the decision maker into considering as wide a range of options as possible, whereas others simply rely on a methodological structuring of the problem to encourage option generation. Below we consider several studies and try to analyze their impact on the problem of option generation and value assessment.

3.1 Studies in Behavioral Psychology

An important attempt to understand the processes by which the decision maker generates alternative, rival hypotheses about the state of the world and thus, by implication, the possible action alternatives is reported by Gettys and Fisher (Ref. 23). In this work the authors develop a model of hypothesis generation in an inference task. They assume a hypothesis retrieval process that consists of a directed recursive search of long-term memory. This memory search is assumed to be triggered by a "plausibility" estimation process and the contention is that new hypotheses are generated only when their plausibility is high enough to make them active contenders for the most likely hypothesis. The basis of their analysis is Bayes Theorem and they claim strong experimental evidence for their theory.

This work has clear implications for option generation and subjective evaluation. Although it does not propose any mechanisms for helping the decision maker it does throw some light on the psychological factors that operate when the decision maker is engaged in the options generation and preliminary evaluation task. If the model is correct, then the decision aid should attempt to enhance the decision maker's ability to retrieve hypotheses and assess their plausibility. The aid should also alert the decision maker of the need to generate new hypotheses if his current set becomes implausible.

The recent work by Pitz, Sachs and Heerboth (Ref. 24) is a direct attempt to understand the factors which influence the individual's ability to generate options. The authors recognize that efficient structuring of the problem is the key to effective options generation, but comment that research which suggests how best to carry out the structuring process is almost totally lacking. They start by asking why a decision maker might omit certain alternatives and consider a variety of explanations that are essentially variations of the availability bias and framing problem (see Appendix A). Their solution is to first ask the decision maker to describe his objectives And then ask what additional choices might be effective in achieving any given objective. They note that while a choice may not be very useful with respect to other objectives, it might be worth considering in the analysis.

To test the validity of their conjecture, they performed a number of experiments in which decision makers were subject to a variety of information conditions. Performance was measured in terms of the number of alternatives generated. Their results clearly indicate that focusing on the decision maker's objectives is an effective way of generating choices. Most interestingly, though, they discovered that the method worked best when the decision maker examined each objective in turn rather than considering all objectives at once.

The generality of the results is obviously limited, but they confirm that it is not sufficient simply to ask the decision maker to describe the choices that are available; steps must be taken to ensure that important choices have not been left out.

There is psychology literature that deals with the ability of groups to generate plans and decision strategies and although this work has tended to focus on the sociology of group dynamics, there are two general themes that are relevant to structuring the option generation and evaluation process.

The first theme is that group decision making using techniques like Delphi (Ref. 25), Social Judgment Analysis (Ref. 26) and Nominal Groups (Ref. 27) can produce judgements that are superior to the judgements of individuals. In all of these methods, the members of a group first generate ther own independent assessments of the problem, then subject these to group review, follow this with individual re-assessment and then iterate until the group converges on some "best" compromise. We might characterize this as a two-stage feedback process. The first stage consisting of a preliminary focusing on important factors by individuals and the second stage being a refinement after group review. The feedback loop serves to stabilize the process and ensure consistency.

The second theme is that the reviewing phase of the process is crucial to the success of the group effort. Much effort has gone into determining the factors which prevent the group from reaching its full potential and, according to Hackman & Morris (Ref. 28), "....the challenge is to identify, measure and change those aspects of the group interaction process that

contribute to such obvious differences in group effectiveness."

In an attempt to define some ways of improving the performance of the group, Schwenk and Cosier (Ref. 29) studied the comparative effectiveness of three approaches which they call dialectical inquiry, DI; devil's advocate, DA; and expert, E. The first of these, DI, involves examining a situation completely and logically from two different and opposing points of view. A structured debate is then conducted in which the two points of view based on the same data are forcibly presented to the decision making group. In the DA approach a "best possible" judgment is made of the problem and then this is critically examined to determine all that is wrong with the judgment and to expound reasons why it should not be accepted. Finally, the expert approach is one in which some part of the group is deemed as expert and allowed to generate its own judgment which the remainder of the group is willing to accept. Schwenk and Cosier examined the group performance in a series of financial prediction problems and determined that under a range of conditions an objective nonemotional kind of devil's advocate is the preferred mechanism for the group interaction.

In summarizing these comments on group decision making, we can see that it is important to have both an iterative structure and a way of challenging the assumptions made by members of the group. In the context of options generation and evaluation, we must conclude that a recursive form of problem structuring and frame modification seems likely to be an effective way of option aiding.

3.2 Studies in Decision Analysis/Computer Science

The digital computer is a natural tool for decision aid implementation and there have been several attempts to build computer systems for decision problem structuring. None of these has option generation and preliminary evaluation as their main aim, but all claim to enhance the decision maker's effectiveness and ability to consider a wide range of decision alternatives.

The first significant attempt to build an interactive aid was by Leal (Ref. 8). His computer program elicits a decision tree from a decision maker in an English-like conversational mode and emulates a decision analyst who guides the decision maker in structuring and organizing his knowledge. The approach centers on the realization that the dynamic process of decision tree elicitation is almost identical to conducting a heuristic search on game trees. Such searches are in the domain of artificial intelligence and permit real-time rollback and sensitivity analysis. Leal's work has been extended and developed into a commercially available group decision aid by Johnston & Freedy (Ref. 30). Tests with the aid (Ref. 31) were apparently successful and among the benefits is the tendency of the group to consider "a larger number of possible events and consequences."

However, this improvement in options generation capability appears almost incidental and is presumably a result of the systematic approach to problem structuring rather than any special feature of this aid. We might conclude that any structuring aid would help generate decision alternatives and that this particular methodology is not especially beneficial.

An interesting proposal for an aid to crisis decision analysis has been produced by Robinson (Ref. 32). Since this has not been implemented, we can only speculate on its effectiveness. However, the crisis decision modeling procedure that he uses is of some interest. The basic skeleton of the model is constructed from a series of decision structuring modules, and since a crisis precludes the development of a complete deterministic model, only the most important alternatives, events, and outcomes are identified. The innovative part of this work is its idea of a hierarchy of templates for helping the decision maker organize and categorize information about the crisis. Robinson claims that "....templates which cover a complete range of conceivable actions encourage the generation of new alternatives." The templating phase is followed by the construction of an influence diagram that represents the probabilistic interaction of the elements of the crisis, the construction of a preliminary decision tree and then expansion of this tree using a standard sensitivity analysis to focus on the most important events. To summarize, Robinson's work does not indicate any significant new insights into options generation, but it does highlight the importance of a systematic structuring in helping the decision maker understand complex decision

problems.

A very detailed approach to decision problem structuring has been taken by Merkhofer, et al (Ref 14). They define decision structuring as "the process of identifying and organizing the factors of a decision in such a way that logic may be applied to identify a preferred decision strategy." Their approach uses a decision tree as the basic model and their aid is essentially a computer-based procedure for rapidly constructing and analyzing this tree. Their approach is to break the problem into two phases: a preliminary structuring which uses systematic inquiry to generate a basic decision tree, followed by expansion of the tree using a detailed sensitivity analysis.

It is in the first phase that they specifically address the identification of decision alternatives. They acknowledge the importance of this problem, and offer a form of templating, which they call a "list of generic alternatives," coupled with a formalization of "devil's advocate" using adverse scenarios, as a way of reducing the likelihood that the decision maker will overlook an effective alternative. In the expansion phase, the focus is on enhancing the decision maker's ability to identify important uncertain events that have been previously overlooked and which are likely to increase the decision model's reliability.

The limited experimental applications of this aid suggest that it is readily accepted by decision makers, that the decision trees produced are relatively simple, that the decision makers have confidence in the solutions, and that the time needed to produce effective solutions is much less than that required using traditional processes. No attempt seems to have been made to assess the impact of the aid on the range of options produced, but we should probably conclude that it has a strong positive effect.

A recent report of a goal directed decision structuring system by Pearl, et al (Ref. 33) is substantially different from the previous studies. Its basic premise is that in many, if not all, real-world applications of the kind in which we are interested, the decision maker does not perceive the problem as a time sequence of decision alternatives and event outcomes. Rather, he sees a static network of influences surrounding issues and factors. Thus,

when the decision maker confronts a complex problem he does not think in terms of the alternatives available to him, but in terms of his desires and concerns. This premise leads the authors to consider an alternative structure for representing the decision maker's knowledge. So instead of the usual decision tree, they use an AND/OR goal directed tree most often found in Artificial Intelligence problem solving systems.

The main structural features of this system are its breakdown of the problem into a hierarchy of goals and subgoals, and the use of a complex form of sensitivity analysis to guide the search through the goal network. The user of the system communicates with the program using a somewhat constrained form of English.

The authors claim that the goal-directed approach is superior in both clarity and purposefulness and that the explicit mention of an objective helps the decision maker evoke unconventional alternatives capable of realizing that objective. We see, therefore, that this aid is passive; it does not prompt for alternatives, but relies on the efficiency of its structuring model to help the decision maker generate his own options.

3.3 SUMMARY

The human decision maker is a less-than-perfect gatherer and processor of information, is subject to a variety of cognitive biases and displays personal idiosyncrasies, all of which impair his ability to make fully considered decisions. In times of stress, these deficiencies are exacerbated leading to demonstrably suboptimal behavior. Our aim is to compensate for these weaknesses by developing a decision aid that will encourage the decision maker to make full use of the information available to him. In particular, we want to ensure that he has the capability to consider a myriad of factors affecting the decision, but not necessarily easy to incorporate into models or decision trees, that he can assess their relative importance, and that he considers a wide range of possible decision options, thereby increasing his chance of making the "best" decision.

Our literature review has uncovered several important factors that influence option generation and evaluation. The psychological studies all attest to their influence and the decision analysis/computer science studies all address at least some of them. However, no one effort has succeeded in drawing together all these factors into a unified approach.

A systematic effort to tackle the option generation and evaluation problem must recognize the following issues:

- the importance of goals and objectives
- the value of structuring the major decision influences
- the impact of questioning and framing
- the ability to highlight critical events
- the essential nature of iteration and feedback

The methodology described in the next sections is an integrated attempt to aid the decision maker in generating and evaluating options. It provides a method for the decision maker to consider each of his objectives in turn, and to carefully structure the elements of the decision that influence them.

4. OPTION GENERATION AND EVALUATION FOR DECISION PROBLEMS

4.1 INTRODUCTION

The actual generation of options in a decision problem is done by humans, who may or may not be prompted by a procedure or automated process. In "easy" decision problems humans have little trouble identifying options and selecting one for implementation; and they do not need or want any aiding techniques. In these situations no system of techniques should be used. In complex decision problems the humans are still likely to immediately think of some options, but may not immediately select any of them. In these more complex situations they may take time to make an effort to better understand the problem, to refine their initial options and note the weaknesses, and to generate entirely new options. This (human) creative process often alternates between quickly looking at many of the decision problem factors from many different perspectives (breadth) and studying a few of the factors, judged the more important ones, more intensely (depth). Procedures, automated processes, and an environment that fosters the clear understanding of the problem space in both breadth and depth should be helpful in prompting the humans to expeditiously generate plausible options in these complex and time critical decision problems.

The general description of steps involved in a decision problem is given in Figure 4.1. The discussion is directed at those elements described in the "dashed" box in Figure 4.1. Once an understanding of the problem, environment, constraints and objectives has been gained, one is at a better position to generate options to be used in a decision analysis effort that results in an implementable plan of action.

4.1.1 Motivation for a Proposed Approach

Concise, complete reporting (be it of intelligence, or journalistic material) has always been concerned with the "five W's" (i.e., what,

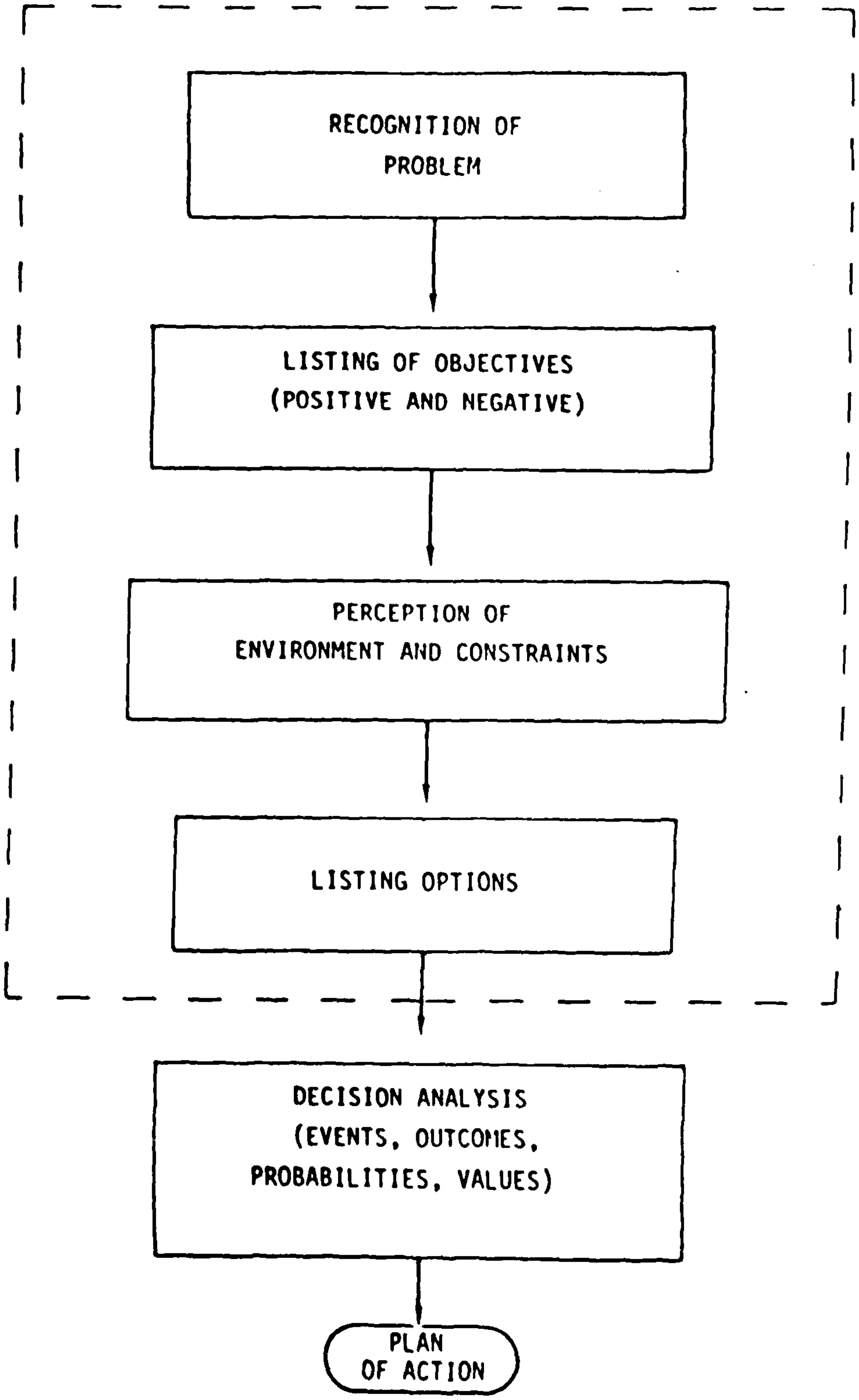

Figure 4.1 Decision Problem Description

why, who, when, and where) and how. These items, when considered, always contribute to the understanding of a problem. Consider, for example, a situation where a Carrier Air Wing commander is charged with planning "a strike mission." What is called for is the generation of options for this strike mission. Out of this set of options, one will be selected for implementation according to some criteria and some decision process. However, the question is still how to generate these strike options. In the generation process the following questions will invariably be asked.

What:	What are we trying to accomplish in this mission?
Why:	Why is this mission required (is it to keep the enemy from achieving his objectives; what are they)?
Who:	Who are we going to engage, or oppose in this mission?
When:	When is this mission planned for (is it a day or night mission; how much time do I have for planning)?
Where:	Where is this strike planned for?
How:	How am I expected to accomplish my mission (will I use my resources; all or part of them; can I rely on reinforcements)?

After all these factors have been considered, understood, and prioritized (e.g., which of our objectives is the most important? which one of the enemy's is most important? which of my resources is most important for my mission? which type of resource should I request? etc.), a strike option that considers all these important elements can be formulated. The difficult part in this planning example is in deciding which factors impact our mission goal in a significant manner and which have a negligible impact. This allows focusing of attention mostly on high-priority elements.

We have designed an approach for option generation and decision factor evaluation that provides a systematic way for considering many decision factors, assessing relative importance for these decision elements, and displaying them in an ordered presentation. This hierarchical presentation provides a good vehicle for (1) keeping a clear understanding as insights are gained from both breadth and depth considerations, and (2) guiding communications among a group of decision makers. This methodology is

integrated with currently practiced decision analysis efforts, followed by a sensitivity analysis. This permits detecting and assessing sensitive events whose occurrence may greatly degrade the performance of our plan of action. This detection of sensitive events allows a "focused devil's advocate" approach to be used in seeking ways (new options or modifying old ones) to improve robustness of our plan. Iterative looping with these new options, when needed, results in a unified methodology for option generation for decision analysis.

Our approach is strongly dependent on a process we call Hierarchical Priority Assessment (HPA). HPA is not discussed in the decision sciences literature for military applications. However we feel that it is an important tool, complementary to many techniques currently under study and in use. HPA is defined in Appendix B and illustrated in Section 5.3 via an application to a decision faced by the Blue task force decision makers in the war scenario of Section 2. The reader who is unfamiliar with HPA is encouraged to read Appendix B now, before continuing through the report.

4.1.2 A Distinction between Decision Analysis and Hierarchical Priority Assessment

A major thrust of our approach is in integrating a priority assessment of decision factors with a decision analysis effort, to attain a unified methodology. At this point it seems appropriate to point out the distinction between "classical" decision analysis and hierarchical priority assessment.

The decision analysis methodology provides a systematic way to choose among alternatives by considering structure of the problem, events, their likelihoods, values/utilities associated with them, and information requirements. However, when faced with a decision problem, the first item the decision maker is required to supply (be it by an analyst, or by a computer prompt) are his alternatives. In contrast, in a similar situation, employing the hierarchical approach, the first question posed to the decision maker is directed at identifying the

problem and his objectives in solving (or addressing) it. Then, further questions identify factors affecting objectives, stakeholders, their objectives, etc. These distinctions are pointed out in Figure 4.2.

This discussion indicates that while the decision analysis methodology is a sound, mature approach for decision problems, it still relies on the availability of alternatives to start the process off. This generation of alternatives can be aided by concentrating on those elements of the problem that impact our goal in the most significant way (e.g., which of our objectives is most important?); this information is provided through a hierarchical priority assessment effort. Therefore, the hierarchical approach to decision problems should not be viewed as a methodology that competes* with (or replaces) currently used decision analysis methods, but rather, augments its capabilities and broadens its scope. For the particular problem of options generation and evaluation, one can say that the decision analysis methodology picks up where the hierarchical approach leaves off.

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*There are cases, though, where this approach provides a complete solution.

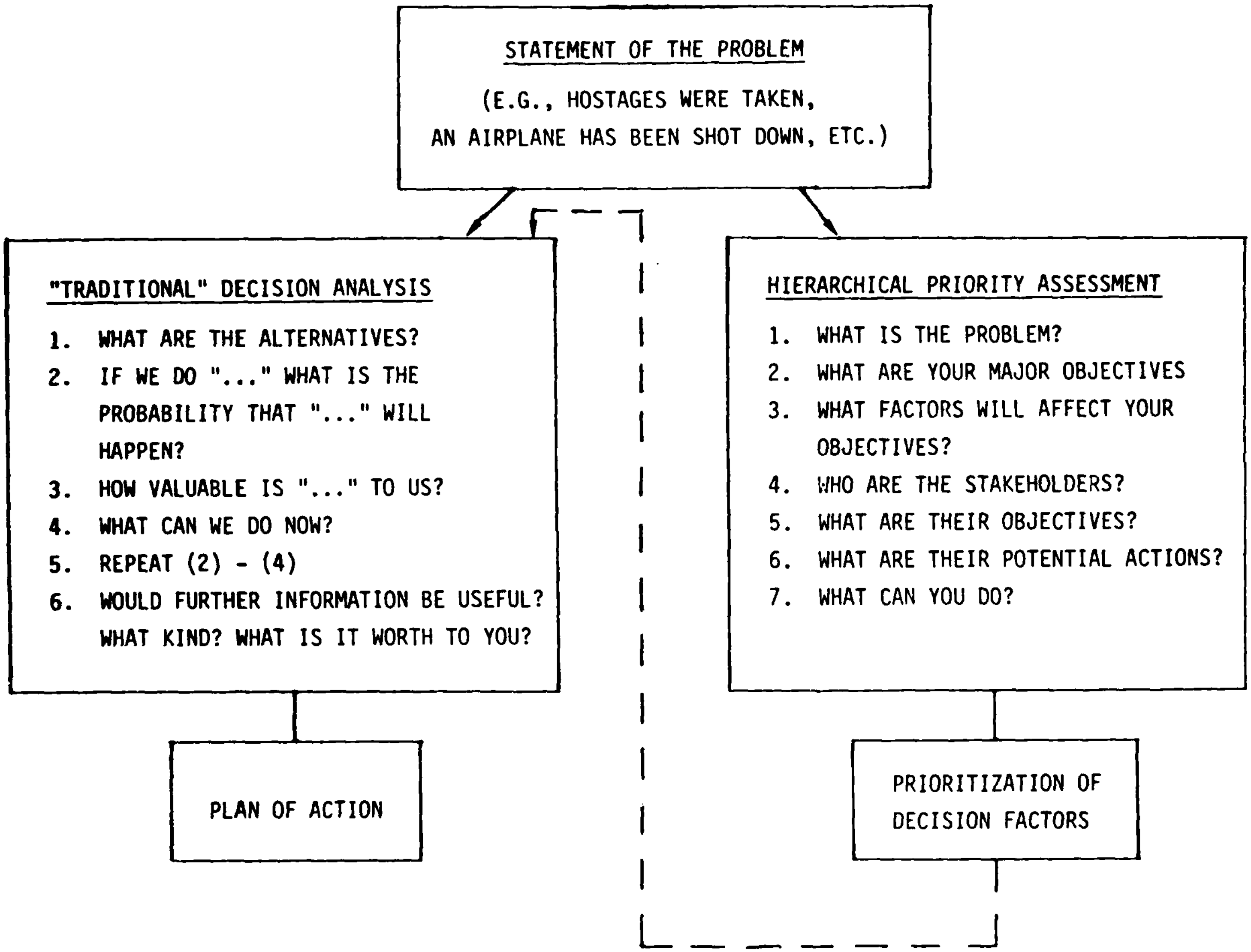

Figure 4.2 Distinctions Between Decision Analysis and Hierarchical Priority Assessment

4.2 TWO-STAGE, ITERATIVE OPTION-GENERATION SCHEME

Our method for options generation and evaluation has two iterative stages that augment a standard* decision analysis process. The first stage (after recognizing the problem) involves the following elements:

(1) Listing of primary decision factors - These may include elements such as the overall goal, our objectives (what are we trying to achieve, what are we trying to prevent), adversary's objectives, stakeholders (who are they), stakeholders objectives (ours and theirs), uncontrollable environmental constraints (e.g., topography, weather, political instability).

(2) Hierarchical priority assessment of primary decision factors - The listing of factors, done in step 1, leads to structuring a hierarchy of these factors. A systematic evaluation is performed next of (1) the relative importance of these factors with respect to associated factors in the structure, and (2) their impact on the overall goal.

(3) Focusing on high-priority elements (decision factors) of the hierarchy - After the hierarchical priority assessment is completed, one can identify those elements in each level with the highest priorities. Then, attention is focused on these elements in generating options (rather than trying to generate options to satisfy, or to account for, all decision factors).

Remark: These steps are discussed in greater detail in the next two sections.

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*This may include either a sequential decision problem represented in a decision tree form, or a Bayesian hierarchical inference; each type needs an initial set of either alternatives or hypotheses.

The first stage provides a focusing mechanism for generating options that address those elements of the problem whose impact on our overall goal is the highest. After this initial set of options is identified, a decision analysis is performed. This step results in a preliminary selection of a course of action. Before this plan is actually adopted (implemented), sensitivity analysis is performed; this constitutes the <u>second stage</u> of our approach. This particular step allows us to identify those low-probability/high-value events whose occurrence can significantly affect attainment of our goal. This step may necessitate performing the decision analysis again (with <u>new</u> alternatives that take care of these sensitive events) or may introduce new factors (such as effect of weather on our objectives) that may have been missed in the first stage; hence, the <u>iterative</u> nature of our two-stage process.

The proposed option generation process is illustrated in Figure 4.3.

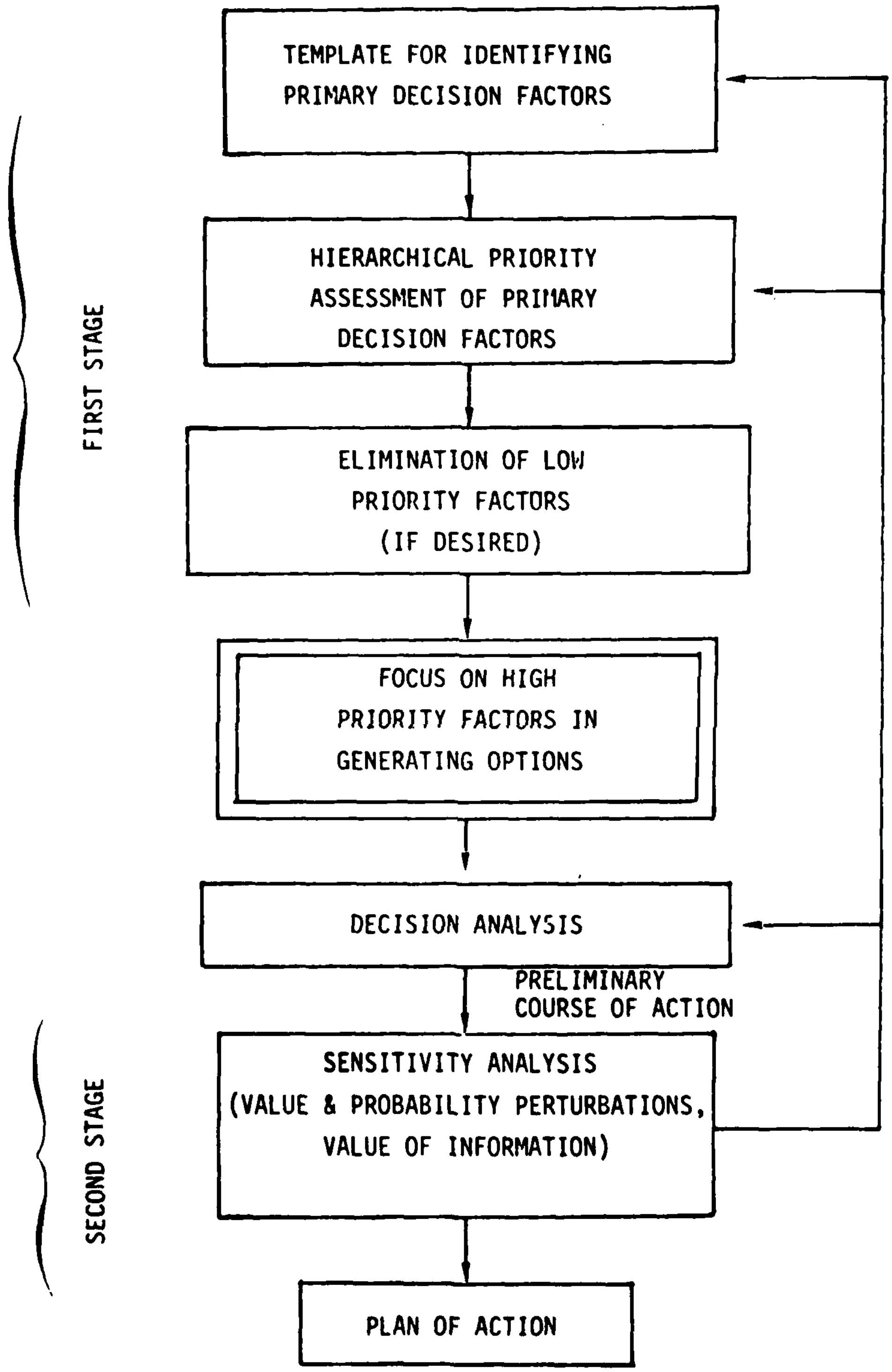

Figure 4.3 Option Generation

4.3 TEMPLATING OF PRIMARY DECISION FACTORS

The first step in the option generation process involves listing of all decision factors that may have a bearing on the problem and its solution. Templating approaches for decision problems have received some attention: Robinson (Ref.32), Kelley, et al. (Ref.34). This templating effort permits classifying, in a structured manner, factors relevant to the problem and its understanding.

Our priority assessment process requires the construction of a hierarchy that lists all relevant decision factors. The hierarchy's apex represents the overall goal in this particular problem. The levels below contain elements of similar description. The order of these levels reflects a logical cause-and-effect relation. The number of elements in each level is affected by the amount of detail desired (e.g., how many objectives do we consider).

The generic hierarchical structure, and the experience gained in using it (Ref.9), provides an excellent foundation for a generic template ideally suited for our purposes. The general format of this template is shown in Figure 4.4. This hierarchical template is generic since its levels are situation-independent; the content of each level will, of course, depend on the particular problem context. This content will be discussed next.

The goal of our decision problem is usually well understood from the context of the problem. This may include statements such as: "project power ashore," "keep the sea lines of communication open," or lower-level goals such as "air superiority in sector A."

The uncontrollable environmental factors may include such elements as weather (frontal activity, poor visibility, etc.), topography, oceanography, and other factors that may affect attainment of our goal.

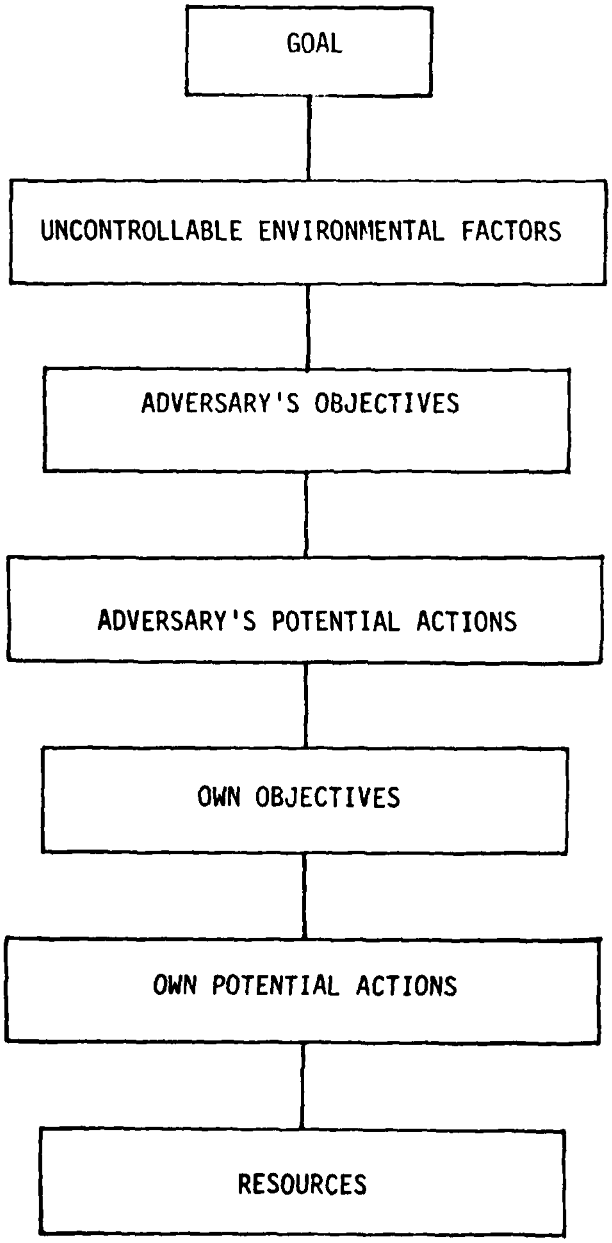

Figure 4.4 Generic Hierarchy (Template) for Priority Assessment

In considering adversary's objectives, one should consider both the enemy's positive (i.e., what is he trying to accomplish) and, equally important, his negative (what is he trying to avoid) objectives.

Adversary's potential actions will consider all possible actions that may be required to support the adversary's objectives (both positive and negative).

In considering our own objectives, one should follow a similar format followed for the adversary, i.e., consider both positive and negative objectives.

In considering own potential actions, we should explore general arenas in which we may use our resources to meet our objectives, counter adversary's actions and deny him his objectives, and finally, attain our overall goal. This level may consider such elements as AAW, ASUW, and ASW actions, special sensor usage, and exogenous force actions.

In listing resources one considers such elements that can support the general actions mentioned above. For example, CV, F-14, CG, FF, SR-71, etc.

Comments

(1) In actual use the analyst, or a computer program, may suggest the general categories to the decision maker and elicit his input of relevant factors in each level.

(2) Different decision makers (or experts) may provide input at different levels. For example, the senior command may provide inputs on our own objectives, while intelligence experts may provide input on enemy's motives and potential actions.

4.4 SENSITIVITY ANALYSIS

This step marks the beginning of the second stage of our options generation and evaluation approach. After generating some options and performing a decision anslysis we have a preliminary plan of action. However, before we actually implement it we should go through a sensitivity analysis to identify weak parts in our plan. Two approaches can be developed for the sensitivity analysis: a deterministic approach and a fuzzy sets approach.

4.4.1 A Deterministic Approach

In this section we are interested in probabilistic events described in Figure 4.7.

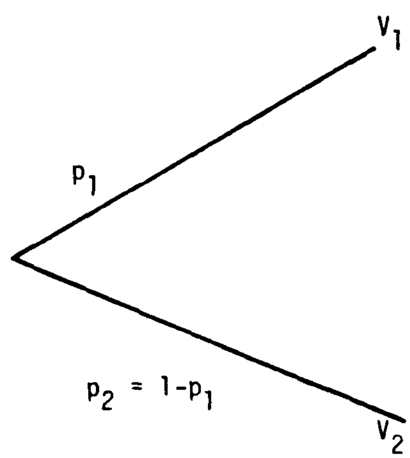

Figure 4.5 A Basic Probabilistic Event

Where p_1 is the probability of occurrence of the event whose value is V_1* and p_2 is the probability of the event whose value is V_2.

Remark: The term "deterministic" used in the heading of this section indicates lack of "hedging" in probability and value assessment. That is, we say "probability is 0.4", rather than say "probability is about 0.4 (or is medium)".

Considering the event in Figure 4.7 we note that the expected value is given by

$$E_1 = p_1V_1 + p_2V_2$$

since $p_2 = 1-p_1$, we have

$$E_1 = p_1(V_1 - V_2) + V_2$$

This expected value is a linear function of the probability p_1; this function, for $V_1>V_2>0$ is shown in Figure 4.8.

Note, in Figure 4.8, that the slope of the expected value line is simply the difference in "tip values" (i.e., $V_1 - V_2$) therefore, the higher the difference the steeper the slope.

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* This value can be taken from a utility function that shows the utility of the particular event.

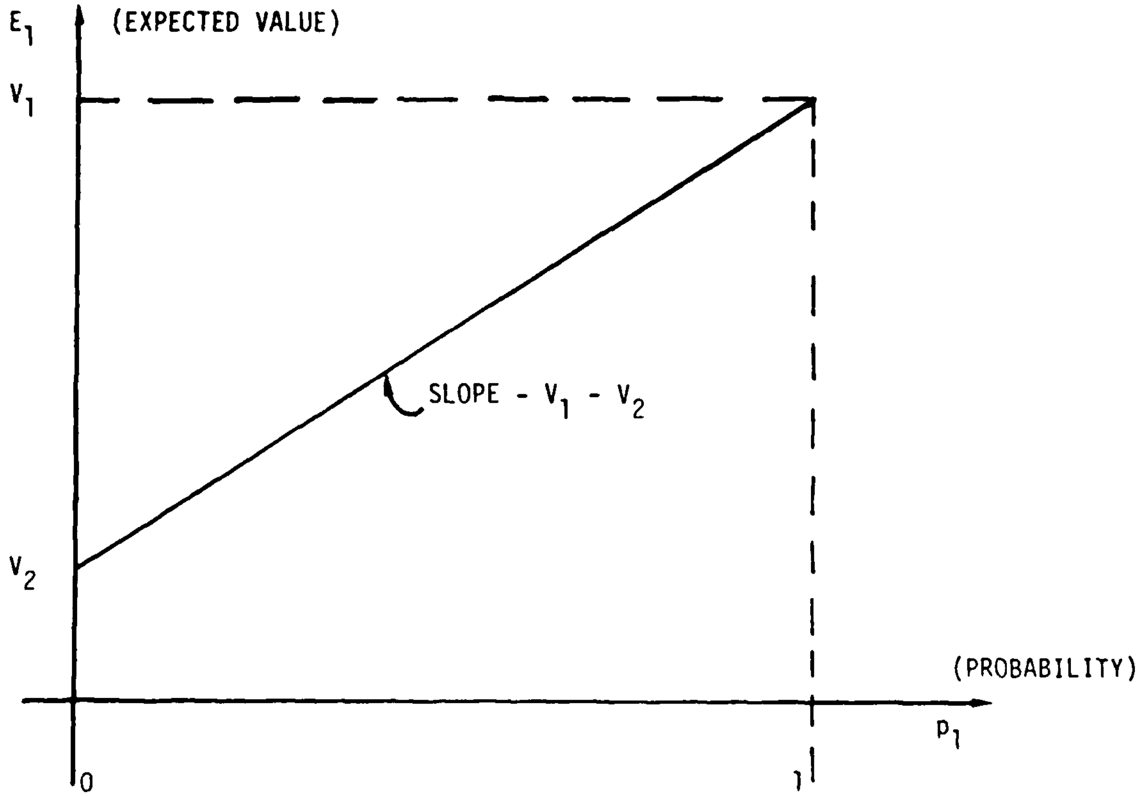

Figure 4.6 Expected Value vs. Probability

Consider now another event described below.

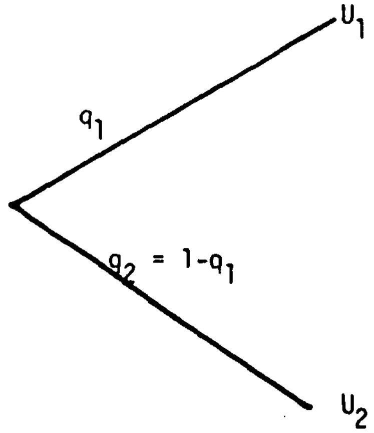

Figure 4.7 A Second Probabilistic Event

The expected value for this event is similarly given by

$$E_2 = q_1(U_1 - U_2) + U_2$$

Figure 4.10 shows the dependence of expected value on probability for both events; it is assumed there that $U_2 >> U_1$, the relation of U_2 to V_2 does not matter much for the point of the discussion.

In considering Figure 4.10, it is evident that there are values for p and q that will result in both events having the same expected value and, therefore, being equally preferred. However, at q_1^* event E_2 may be equally preferred to E_1 (assessed with probability of occurrence p_1^*) but any slight assessment error in q_1^* will result in a significant change in expected value for this event due to the steepness of the slope of the E_2 line relative to the E_1 line; i.e., event E_2 is much more sensitive to small assessment errors than is event E_1.

Our approach considers those events whose sensitivity to assessment error may significantly affect our plan of action. This is a form of a "devil's advocate" approach. However, instead of looking at every possible event and asking "what if" questions, we concentrate only on those events that display a sensitive behavior. This increases efficiency in our approach (especially important under time constraints).

Identification of these sensitive events allows one to seek ways to reduce sensitivity which requires iteration on our basic options and either enlarging the set or modifying it to eliminate sensitive events.

4.4.2 A Fuzzy Sets Approach

The approach described in the previous section is a way of assessing the impact of errors on the decision problem and also a way of guiding

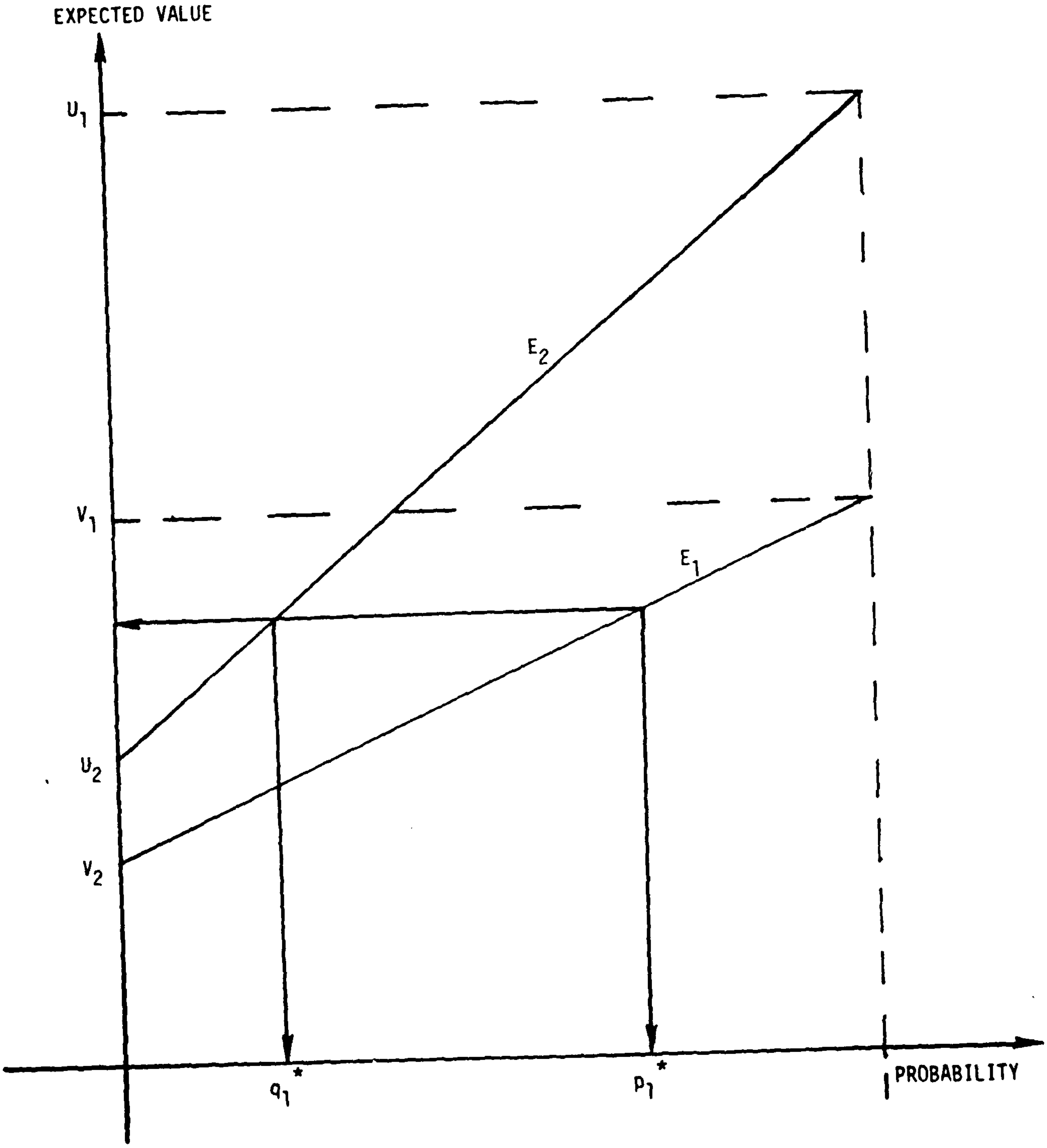

Figure 4.8 Comparison of the Two Events

the decision maker in his search for novel decision alternatives. Since the source of the uncertainty is the decision maker's inability to make precise estimates of event probability and outcome values, we should be concerned with modeling this imprecision in the most appropriate way.

Fuzzy set theory, and more specifically, the theory of fuzzy numbers, offers a way of directly representing and manipulating the uncertainty and permits a sensitivity analysis to be performed in a very effective way. The central idea is that in time constrained and novel decision situations, the decision maker will be unable to express his evaluation of the problem in anything other than linguistic terms. Given that this is the best he can do in the circumstances, we shall use fuzzy numbers as a model of this qualitative information and fuzzy arithmetic as a tool for computing the affect on the overall problem.

Consider the decision problem shown diagramatically in Figure 4.11 This simple binary decision tree depicts the problem of choosing between actions A and B. If we choose A, then there is a probability p of an outcome with utility U_1 and a probability $1-p$ of an outcome with U_2. Conversely, if we choose B, then there is a probability q of an outcome with utility U_3 and a probability $1-q$ of an outcome with utility U_4.

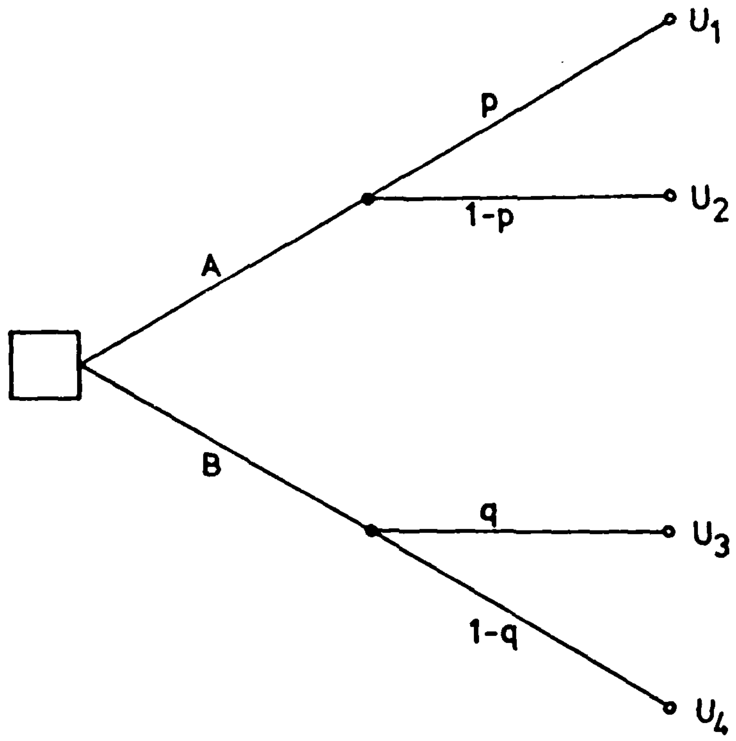

Figure 4.9 A Simple Decision Problem

Using the theory of expected utility, we should choose A in preference to B if and only if

$$pU_1 + (1-p)U_2 > qU_3 + (1-q)U_4$$

If p, q, U_1, U_2, U_3 and U_4 are known precisely then the choice is clear. If, however, some, or all, of them are only imprecisely known then the choice becomes "fuzzy". We can formalize this imprecision by assigning fuzzy numbers to the probabilities and utilities in accordance with the qualitative information we get from the decision maker.

Suppose, for example, the decision maker is able to assign exact utilities to the outcomes but cannot fix the probabilities any more

accurately than some linguistic assessment such as "better than even" or "rather low". If p and q are interpreted as fuzzy sets perhaps as shown in Figure 4.12, then the result of fuzzifying the expressions for the expected utility of A and B will be a pair of fuzzy sets something like the ones shown in Figure 4.13.

The actual mechanism for calculating E(A) and E(B) is straightforward. What is important in terms of a sensitivity analysis, however, is the amount of overlap between the two sets. In fuzzy set theoretic terms, we are interested in the intersection of E(A) and E(B). This is labeled S and shown shaded in Figure 4.13 . Clearly, if S is empty then there are no values of p and q that will change the decision. The decision maker can be confident that although he has not been able to specify the probabilities precisely, he has sufficient information to make the correct decision.

However, in the case where there is overlap, the actual shape of S is an indicator of the sensitivity of the decision. The support set of S, S_o, is an indication of the range of outcome value changes that might occur and the height of S, h(S), is a measure of the degree to which this outcome changeover is possible.

The information we get from S can be used in several ways. We could use it to focus on the fuzzy probabilities and utilities that contribute most to the overlap, thus prompting a series of questions designed to refine the estimates. Or we could simply use it to alert the decision maker of potentially critical areas of the decision problem structure. In most cases, it will be the combination of support set size and height that is important. So we can imagine that a large S_o with a low h(S) might generate an alert of the form "there is some evidence for a large

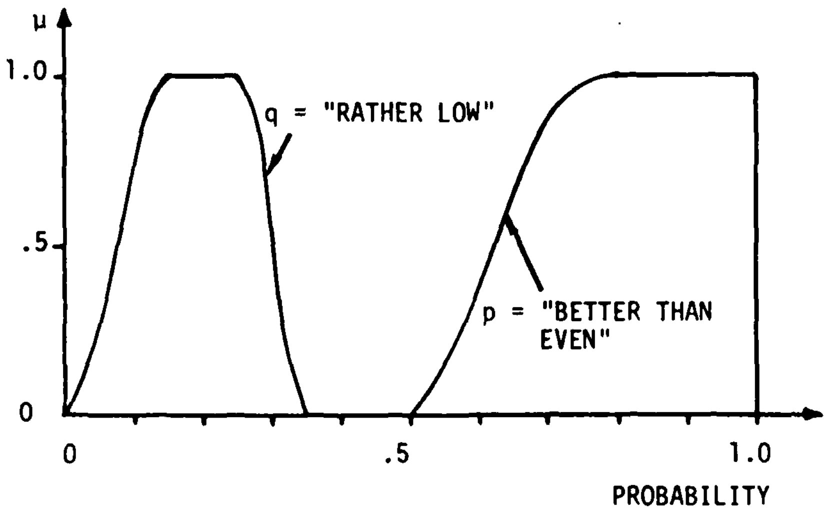

Figure 4.10 Fuzzy Probabilities

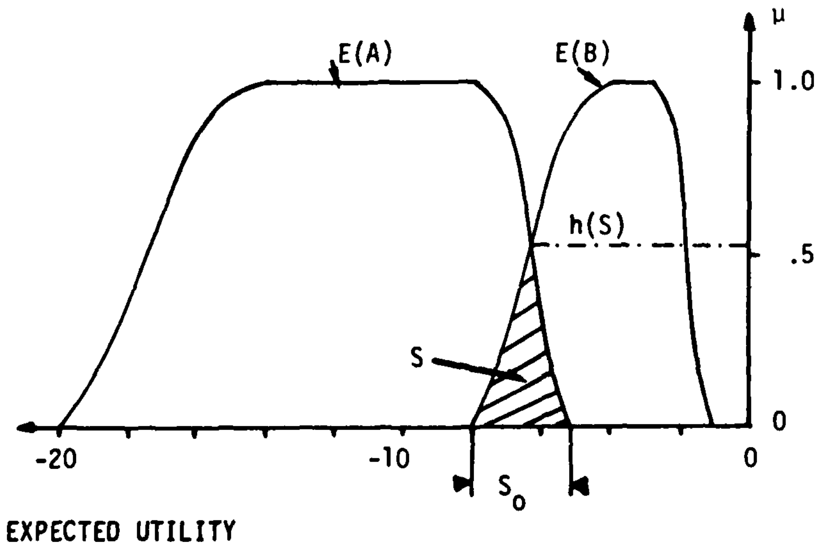

Figure 4.11 Fuzzy Expected Utilities

outcome changeover, suggest further modeling". Whereas a small S_o with high $h(S)$ might generate "strong possibility of outcome changeover, but may not be significant".

We may also get valuable information from noting the size of the support sets of $E(A)$ and $E(B)$ themselves. If they get very large, then this may be an indication of the need for more detailed modeling, irrespective of the overlap. As the analysis in the previous section indicates, large variations in the value of $E(A)$ and $E(B)$ are due mainly to outcomes with high value. This is true in the fuzzy analysis as well, where the effect of these high values is to magnify the uncertainties in the probability assessments.

The main advantage of the fuzzy approach to a sensitivity analysis is that it does not require the decision maker to give precise estimates of the event probabilities and outcome values. It is sufficient that he can give a verbal description of his assessments. While the mapping of these linguistic values into fuzzy numbers if rather subjective, this is not a disadvantage. Indeed, we are not looking for detailed precise calculations, but rather for an indication of the sensitivity of the problem. It is by pointing out potentially critical areas to the decision maker that we hope to lead him to consider other alternatives. During this dialogue it is not necessary, nor desirable, to be very specific and so we feel that the fuzzy set theory view of vagueness is particularly appropriate.

4.5 ITERATION

The discussion of our method has now reached a point where both stages of the option generation and evaluation scheme were presented. The first stage compiled a list of primary decision factors and assessed their impact on the overall goal. This allows the decision maker to focus his attention on those high priority elements and this, combined with the insight to the problem gained during the pairwise comparison session, allows him to come up with an initial set of options. These options are then evaluated by a decision analysis approach to indicate a preliminary plan of action. In the second stage, sensitive events are identified and corrective measures to reduce their impact on performance are sought. These corrective measures are either in the form of a modification to existing options, or by introducing new decision factors. Modifying existing options will result in repeating the decision analysis step as is implied by the small iterative loop in Figure 4.3. Introducing a new decision factor (such as weather effects; e.g., storms) will require reassessing the priority of this new factor and examining whether it creates any shift in priorities. This step is implied in the outer (bigger) loop in Figure 4.3. Thus, the <u>iterative</u> nature of our approach acts to <u>stabilize</u> the outcome of the options generation effort. That is, after a few iterations and re-examinations, no new options have been raised and all sensitive events have been identified and handled.

5. VALUE ASSESSMENT IN A TASK FORCE DECISION ENVIRONMENT

5.1 INTRODUCTION

Decision problems at the task force commander (CTF) level involve problems that are complex and, at times, critical. This complexity together with complicating factors such as time pressure and stress associated with decision environment may degrade the quality of the decision process itself. This general background motivates the effort directed toward developing decision aids for the CTF and his staff.

Decision aids developed thus far resulted in models describing recurring situations such as emission control and transit planning, as well as structuring aids for general decision problems. The problems considered in the second class are those that can be addressed and solved through a decision tree formulation. Such decision problems are solved after developing the structure appropriate to the problem itself. This structure may start with a general identification of cause and effect (influence diagrams) which leads to a decision tree description. Next, probabilities have to be assessed for the various events described. Last, by assigning certain values to anticipated events, a preferred course of action can be prescribed.

The question of value is addressed through the concept of utility. This results in numbers being assigned to outcomes that permit their evaluation. This utility function is assessed by talking with the CTF and members of his staff, and used as a true representation of their choice-making, risk-taking attitudes whenever a choice has to be made in the decision process. This utility, or value function, is supplied as input to the process and subsequently used in various decision problems.

In considering various decision making scenarios it is easy to see deficiencies in this approach of supplying a value function <u>external</u> to the decision problem. As an example, consider the value associated with two types of airplanes, say an F-14 and an A-7. One may be tempted to compare firepower, speed, and general sophistication and conclude that the F-14 is, say, four times as valuable as the A-7. While this conclusion may hold true in most

situations, it should not be accepted as the universal value assessment. This is so because there may be certain missions (e.g., tactical air strikes) for which the A-7 will be far more valuable than the F-14.

This section presents another approach towards value assessment in the task force decision environment. The approach organizes the value problem into an hierarchy that considers all the factors that are relevant to the value question. The end result of this hierarchical value assessment approach is a task-dependent value function (rather than an external input).

5.2 A TASK FORCE DECISION ENVIRONMENT

The Naval task force decision environment described in reference [1] highlights the fact that decision processes followed by task force commanders vary from one CTF to another. In very simple decision problems the decision may just be a snap judgement with no structured process (even though it obviously draws on the CTF's past experience). In other simple, yet routine, decision problems an old operational order can be used as a guideline in drafting a new one to meet the particular situation at hand. General guidelines for decision making in more complex situations are offered in various naval publications.

In complex, nonroutine decision situations the approaches mentioned above cannot be relied upon in formulating a course of action. Even the availability of naval publications like NWP-11, and others, cannot be relied upon as a sole source of aid in these complex situations. When under time pressure it is likely some factors or options will be ignored and a picture of a limited scope used for decision making (optimizing vs. satisficing). Also, in these cases we may have what is known as "judgement by availability" (Ref.11). When under time pressure and in a generally stressful environment decision making and judgement ability may be greatly degraded. These factors are the general motivation for developing operational decision aids to be used by the CTF and his staff.

The main responsibility of the CTF is in formulating and executing a plan of action called upon to meet a certain perceived situation. This decision environment is depicted in Figure 5.1.

The decision aids depicted in Figure 5.1 interact with the CTF and members of his staff to elicit inputs that will allow the formulation of a plan which is the end product of this particular decision process. The basic elements of this process are discussed below.

The perceived mission and its environment (time pressure, criticality,

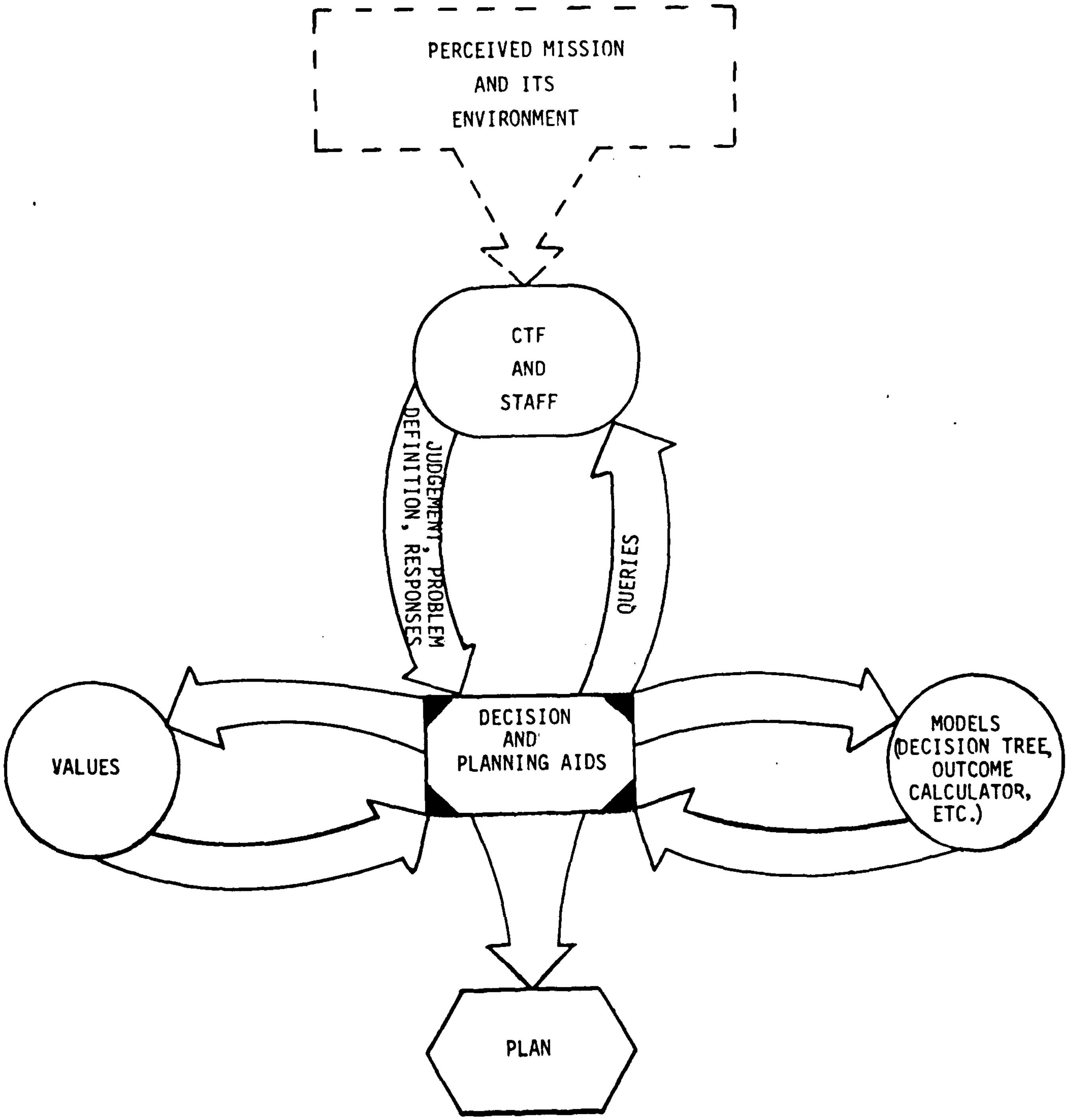

Figure 5.1 The Task Force Decision Environment

past experience, etc.) are major factors affecting the decision and judgement qualities of the CTF and his staff. This particular block is drawn in broken lines in Figure 5.1 to indicate that it is not an explicit element of the process but it does contribute to the overall quality of the decision process.

The interaction between the decision aid and the CTF and his staff is done as follows. The CTF defines the general decision problem to be considered (choice among options, priority assessment, planning, resource allocation, etc.). The decision aid, through prompts and queries, elicits various inputs from the CTF and his staff in the form of requests for judgement. The prompts and queries in a well designed aid, will follow a logical sequence that is particular to the decision problem stated initially by the CTF. For example, in the case of a choice among options, one may be interested in developing a decision tree description of the system. The decision aid should follow a sequence of queries directed toward eliciting, in an interactive step-by-step manner, the particular structure as envisioned by the CTF. Attempts toward this kind of computer aided structuring of decision problems have been reported in references [8] and [14]. The result of the effort in this stage is a "model" that attempts to describe the situation faced by the CTF. The particular model developed may vary, and may include submodels such as decision trees, a strike outcome calculator, EMCON planning aid, etc.

The development of a model, detailed as it may be, does not lead immediately to a plan of action. The reason for this is because the situations described in the model are evaluated according the some value scale. Utility theory was developed and successfully applied in many decision problems. However, military situations offer a class of problems where a utility function cannot be developed "off-line" in a manner disjoint from the problem under consideration. For example, in considering short-range defensive operations (e.g., defense of main body of task force) an F-14 may prove to be of much higher value than an A-7. In contrast, in considering an air strike this value assessment may reverse itself. This simple example demonstrates the need for a utility model to be developed in conjunction with the model for deriving the plan of action.

The plan of action which is the end product of this process is directed toward solving the problem faced by the CTF. Specifically, this may include types and sequences of military actions, force compositions, and resource allocation.

The approach taken here toward the development of a utility model is through the development of hierarchical priority assessment schemes that are task-oriented. This priorities model can then be incorporated into, for example, a decision structuring process (such as reported in reference [14]) to yield an integrated, robust, decision aid.

The technical foundations of the proposed approach are detailed in Appendix B. An illustrative example of its application to a task force decision problem arising in the war scenario of Section 2.2, is given in the next section.

5.3 VALUE ASSESSMENT

The approach described in Appendix B for priority assessment can be adapted to the problem of value assessment. This is accomplished by constructing an hierarchy that describes the various factors affecting the task force mission goal. Typically, such an hierarchy will have various levels, whose specific description is part of the value assessment process. These levels may include the following:

- Task force mission goal (the apex of the hierarchy)
- Scenarios
- Major task force objectives
- Evaluation yardsticks
- Operational options
- Components of value function (e.g., resources).

This particular hierarcy is depicted in Figure 5.2. The specific detail associated with each level may be different from mission to mission which, in turn, may result in a different prioritization of the elements. The bottom level of the hierarchy includes those elements whose relative importance the CTF has to evaluate in certain situations.

For example, in considering an air strike against some enemy land targets the (through outcome strike calculators or judgement) may anticipate certain losses in, say, F-14 and A-7 airplanes. The particular plan to be chosen and implemented will be the one that, in addition to achieving the mission will also minimize the expected loss. This last objective requires the availability of a value scale that will allow the relative importance of the F-14 or A-7 relative to the overall task force mission goal. A form of a value function to be considered is a linear† relation given by

$$V = w_1 x_1 + w_2 x_2 + \ldots + w_n x_n , \qquad \sum_{i=1}^{n} w_i = 1 \tag{5.1}$$

where

w_i = relative importance of i-th value component

x_i = i-th value component.

† Other forms may also be considered.

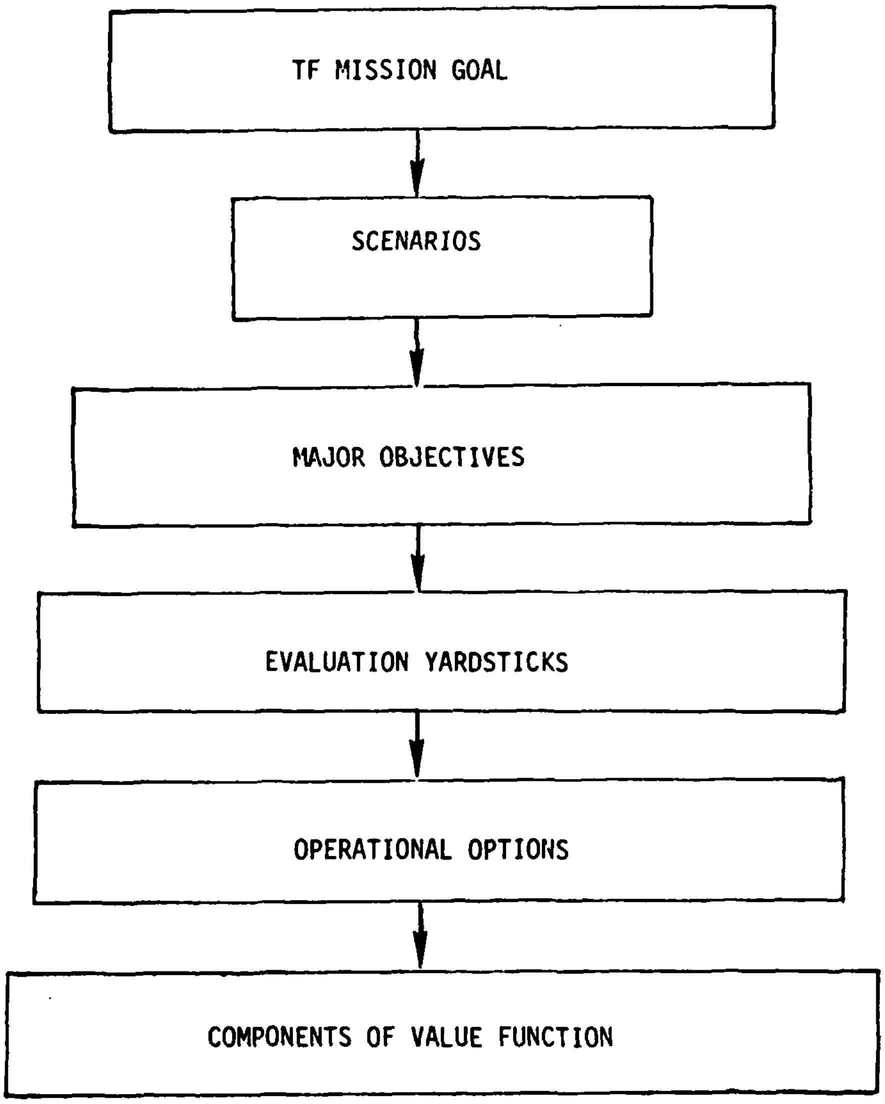

Figure 5.2 Hierarchical Value Assessment

In the particular example mentioned above, this value function may look like

$$v = -w_1 x_1 - w_2 x_2$$

where

x_1 = number of expected F-14 losses

x_2 = number of expected A-7 losses

w_1, w_2 = relative importance of F-14 and A-7

In a particular situation the CTF may consider the F-14 three times more important to his overall mission than the A-7; this will result in his value function having the form

$$V = -0.75x_1 -0.25x_1$$

Then, whenever the particular loss assessment is supplied (i.e., values for x_1 and x_2) one has a particular value number associated with the specific situation being evaluated.

The value assessment method to be developed here is directed toward obtaining the weights, w_i, associated with the components of the value function described in (5.1) . These weights are going to be the priorities associated with the elements of the bottom level of the hierarchy described in Figure 5.2.

The specific levels described in Figure 5.2 may have different members, in different situations. An aid in specifying these levels may be provided through a "Value Component Template" such as the one described in Table 5.1. The list of items considered in each category should not be taken to be all-inclusive. This list may be offered to the CTF and his staff as a suggestion for consideration. They may check off those items found relevant to the particular situation at hand and, when necessary, may include other elements worth considering.

After checking off those elements relevant to the specific problem at

Table 5.1 Value Components Template (Preliminary)

SCENARIOS	• POLITICAL CONDITION • PHYSICAL ENVIRONMENT	
MAJOR OBJECTIVES	• OPERATIONS • SURVIVAL • TRAINING/READINESS	
EVALUATION YARDSTICKS	• LIVES • EQUIPMENT • TIME SCHEDULE	• MORALE • PEER EVALUATION
OPERATIONAL OPTIONS	• AIR STRIKE • NAVAL BLOCKADE • AMPHIBIOUS	• SHOW OF FLAG • SPECIAL FORCES • INTELLIGENCE
COMPONENTS OF VALUE FUNCTION	• TYPES OF AIRPLANES • TYPES OF SHIPS	• SPECIAL EQUIPMENT • PERSONNEL

hand, one may arrive at the value hierarchy described in Figure 5.3. The end result of this analysis will be the relative importance associated with the components of the value function; in the case of Figure 5.3, these components include F-14, A-7, DDG and a CV. The knowledge gleaned from this process can then be used in assessing various courses of action.

An important aspect of this value assessment process is the way one elicits pairwise comparisons judgements. This process can be automated by asking the CTF and members of his staff to check off the appropriate position in Table 5.2 that indicates how activity A_1 compares with A_2 relative to the property mentioned on top. If one considers A_1 to dominate A_2 then the space to the left of the "Equal" category should be used. If A_2 dominates A_1 the space on the right will be used. Whenever a particular column is checked off, say "strong", one can then use Table B-1 to assign the particular numerical value associated with this judgement (5 in this case).

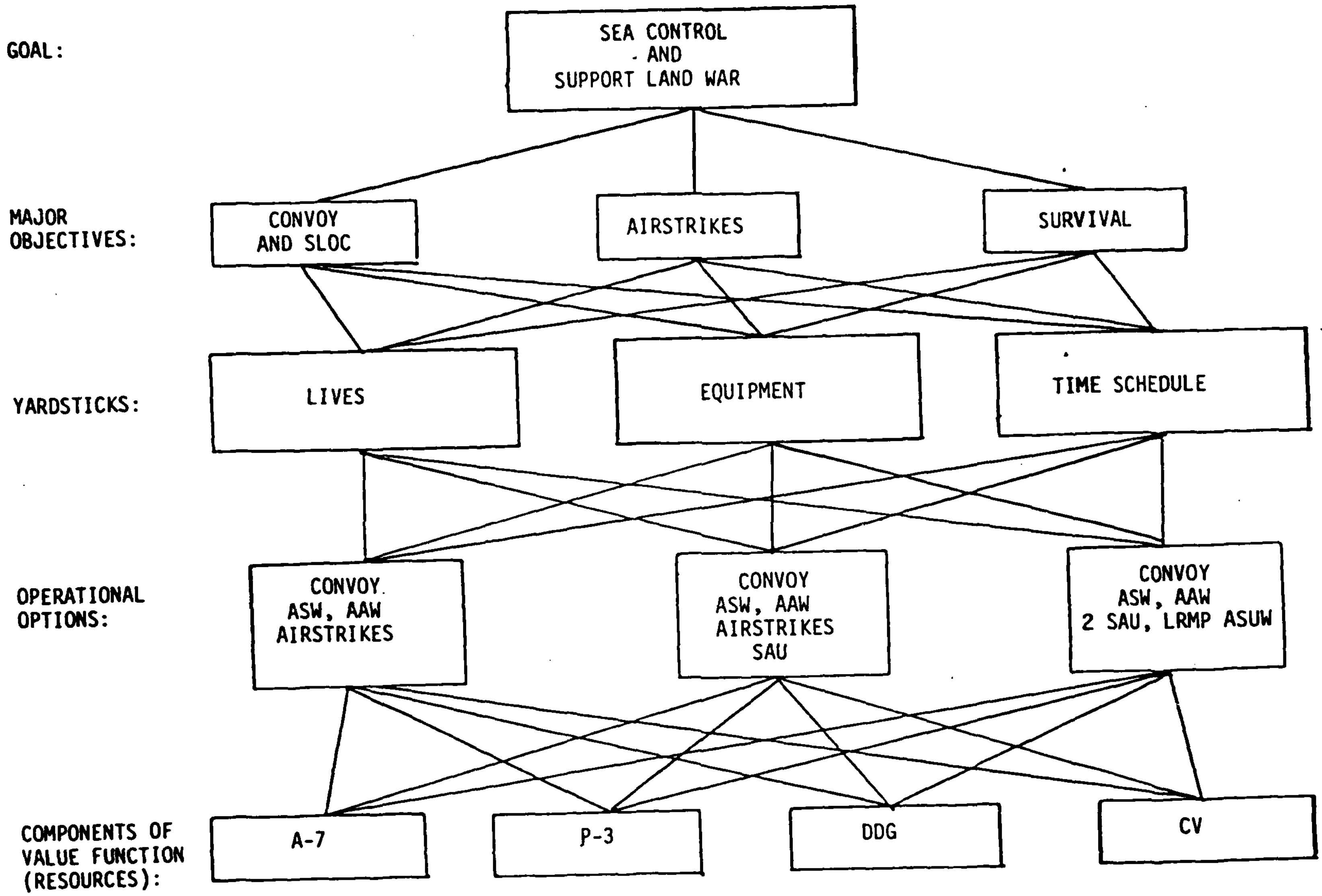

Figure 5.3 Hierarchical Value Diagram - An Example

Table 5.2 Comparison Judgement Elicitation - A Sample Questionaire

COMPARISON
RELATIVE TO: ____________

SUBJECT OF COMPARISON	ABSOLUTE		VERY STRONG		STRONG		WEAK		EQUAL		WEAK		STRONG		VERY STRONG		ABSOLUTE	SUBJECT OF COMPARISON
A_1																		A_2

5.4 SUMMARY

This section and Appendix B presented an approach towards the derivation of a value function to be used in decision problems faced by the CTF and his staff. This value function is task-dependent and may vary from one decision environment to another. This specificity is what distinguishes this approach from others where the value function is developed external to the decision problem.

The actual derivation of the value function is through an hierarchical priority assessment that allows the consideration of all factors relevant to the value issue. This process, in addition to structuring the value function, also indicates priorities associated with various factors. These priorities associated with intermediate levels are useful in their own right. They can be used in the planning stage to identify factors most important to the task force mission goal.

Further developments should address the following issues:

1. Hierarchical Manipulations: How will the final result be updated when new levels, or new members in a level, are added to an existing hierarchy?

2. Group Decision Making: How can this hierarchical approach be used in hierarchical group decision making situations, such as the formulation of a plan by the staff to be presented to the CTF.

3. Feedback between Levels: How is a circular (feedback), cause-and-effect relation between levels being resolved?

4. Use of Results: The results of a hierarchical study are priorities associated with activities, or attributes, in various levels. These, at times, are the answer to a particular decision problem. They can also be used as inputs to a cost benefit analysis in a resource allocation problem.

The development of the value model as presented here can be integrated into a decision tree structuring approach to yield a unified methodology that is task-specific, and does not use pre-structured models.

APPENDIX A
PSYCHOLOGICAL CONSTRAINTS AND INSIGHTS

The problem we are addressing in this appendix is how to aid the human decision maker, or group of decision makers, in recurring situations or situations of high stress. This stress may be induced by the nature of the problem ("life or death situations"), the need to make a decision in a short space of time, the lack of historical precedent or a combination of all these. In such situations, decision makers display reduced information search capabilities, consider fewer decision alternatives, over-react to isolated pieces of information and generally engage in what would otherwise be suboptimal choice generation and selection.

Our purpose is to help the decision maker overcome these deficiencies by designing an aid that offsets his tendency to ignore or inadequately consider viable decision alternatives. The reasons for this suboptimal behavior have not been resolved, although various attempts to develop theories of stressful decision making have appeared (see Ref. 10, for example). However, two important factors are the systematic cognitive biases exhibited by the decision maker and his personal decision making style. In the remainder of this appendix we shall review the effects of cognitive bias in stressful decision making and offer some comments on the importance of matching the decision aid to the personality of the decision maker.

1. COGNITIVE BIASES IN DECISION MAKING

There is an extensive set of literature concerned with the effects of cognitive bias in decision making (see Ref. 11 for a review) and it is not our intention to repeat that exercise here. Rather, we want to examine some of the biases that seem to impinge directly on the decision process. We are most concerned, therefore, with those biases that limit the information gathering capability of the decision maker and those which prevent him from considering all the implications of the information that he has received.

In a stressful (or repetitive) decision environment, the decision maker tends to focus quickly on those parts of the problem that he believes he

understands and then allows his subsequent actions to be biased by his narrow view of the problem scenario. This is, in effect, a form of judgment by availability. That is, an assessment of the situation based on its perceived similarity with other decision situations. This may be valuable in the training context, but too restrictive in "real world" situations. One feature of any "real world" decision aid, therefore, should be a facility for presenting the decision maker with a wide range of possible contexts for the decision problem.

Closely related to this difficulty is what may be called the selective perception bias (Ref. 12, 13) in which decision makers bias their recollection and interpretation of information so that it is consistent with their view of the problem. This can lead the decision maker to exclude information that actually points to alternative problem formulations. A particular example of this is the construction of mindguards (Ref. 14) in which decision makers tend to limit or distort their world views so as to produce a less threatening perception of difficult situations. An option generation aid then, must ensure that the decision maker does not ignore potentially useful information and perhaps should force the decision maker to give reasons for his interpretation of the data.

Another important problem is that, except for some Bayesian inference tasks, people tend to be overconfident in their judgements. Indeed, decision makers will often give wrong answers with certainty. This phenomenon, called the certainty illusion by Slovic (Ref. 15) is important to understand because it prevents the decision maker from giving full weight to possible alternatives. One reason for this overconfidence is that the environment is not structured to show the decision maker's limits. Sometimes the decision maker receives no feedback at all and is therefore unable to detect the errors in judgment. Even when he does, selective perception may prevent him from modifying his assessments in the appropriate way. In the context of a decision aid then, we should ensure that the decision maker does work in a sufficiently structured environment and that his confidence in his decisions is tested against appropriate norms.

Finally, and perhaps most importantly, there is the issue of what Tversky and Kahneman (Ref. 16) call the framing problem. In their attempts to extend the expected utility model of decision making under risk, they became aware that different formulations of the same problem can produce predictable shifts of preference. By a decision frame they mean "....the decision maker's conception of the acts, outcomes and contingencies associated with a particular choice. The frame that a decision maker adopts is controlled partly by the formulation of the problem and partly by the norms, habits, and personal characteristics of the decision maker." Thus, a decision aid could hopefully be expected to present the decision maker with alternative descriptions of the problem and to be alert for changes of preference that might lead to novel decision options.

2. COGNITIVE STYLES IN DECISION MAKING

While decision makers have certain types of cognitive bias in common, they differ widely in what we can call decision style. This concept is rather vague although Levit, et al (Ref. 17) define it as "the characteristic and self consistent way an individual uses information in the decision making process." Attempts to define taxonomies of decision style are usually based on sets of decision maker attributes that influence this style. Thus, MacCrimmon and Taylor (Ref. 18) discuss four attributes, namely perceptual ability, information capacity, risk taking propensity and aspiration level, and their influence on the decision strategies adopted by decision makers.

This set of attributes is by no means unique and a central issue here is the exact set of attributes that should be used. The evidence seems to be that a useful set can only be determined in relation to the problem at hand. For example, Taylor and Dunnette (Ref. 19) used sixteen "reasonable" attributes in an attempt to characterize managers in a manufacturing environment while Crolette & Saleh (Ref. 20) used seven attributes to describe decision makers considering tasks in the Marine Corps.

Perhaps more relevant in the context of decision aids are the attempts by Levitt, et al (Ref. 17) and Johnson (Ref. 21) to develop a taxonomy which reflects user needs rather than underlying personal characteristics. Levitt,

et al have three dimensions of decision style, namely abstract/concreteness which relates to the information acquisition process, logical/intuitive which relates to information assimilation, and active/passive which relates to action selection. Johnson has two dimensions: internal/external which parallels Levitt's abstract/concrete, and systematic/spontaneous which parallels logical/intuitive.

In an instructive extension of Johnson's concept, Wohl (Ref. 22) has examined the question of the extent to which decision aids must be made adaptive to individual decision styles. He concludes that there are a few guidelines but little substantive research. Levitt, et al, on the other hand, seem very clear in their belief that decision aids should be adaptive to various decision styles.

The difficulty is that the impact of decision aiding technology on various decision styles is largely unknown. Thus, although Wohl suggests that the external style decision maker can be expected to ignore automated aids in favor of human "sounding boards," and that the internal spontaneous decision maker requires a decision aid that is a learning experience, this is merely speculation. There do not seem to be any consistent ways of viewing decision style and, if we accept Wohl's point of view, any decision aid that we build would have to have considerable flexibility.

A question that does not seem to have been addressed is whether, and to what extent, the users of a decision aid can be trained to take advantage of its features. In the case of a decision for the commander of a task force and his staff, we would expect the users to be well educated and able to grasp the principles behind the aiding. We might suppose therefore, that some of an aid's deficiencies might be counteracted by the human decision maker's adaptability.

APPENDIX B

HIERARCHICAL PRIORITY ASSESSMENT (HPA)

The hierarchical priority assessment scheme presented here is based on Saaty's approach to hierarchical decision problems (Ref.9). The basics of this approach will be reviewed here and used in an illustrative naval decision problem in the next section.

In the Analytic Hierarchy Process approach, the decision problem is decomposed into levels containing objects with similar attributes (e.g., a level describing objectives and a level describing policies designed to meet these objectives). The approach is directed toward assigning priorities for each member in a particular level. In particular, one is interested in ways to propagate the priorities of each level throughout the hierarchy to establish priorities in a particular level of interest.

Consider, for example, the situation described in Figure B-1.

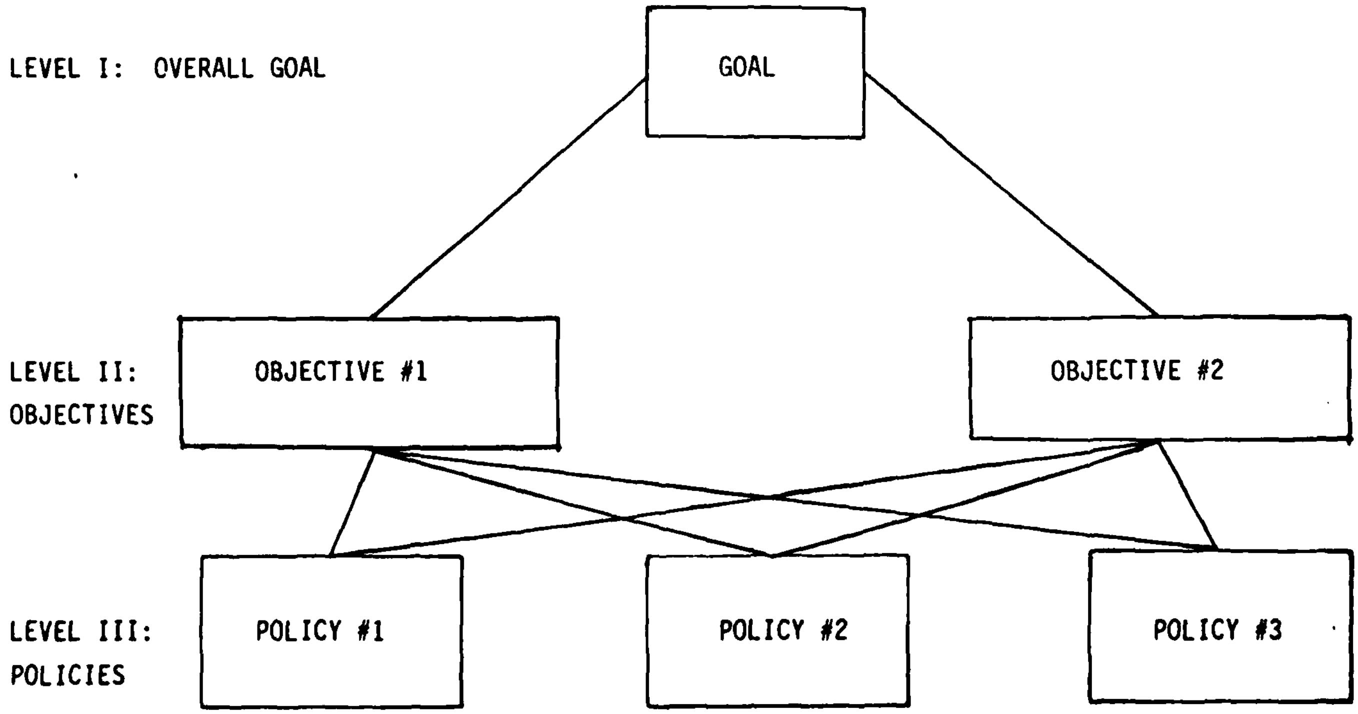

Figure B-1 Hierarchical Policy Evaluation

The decision maker has to evaluate the relative importance (priorities) of the 3 policies under consideration; this, in turn, will help him later on in allocating resources to implement these policies. The policies themselves are designed to meet certain objectives (two in this particular case) that contribute to the overall goal the decision maker is trying to attain.

In constructing hierarchical structures other than the one shown in Figure B-1, the following guidelines should be remembered:

1. The number of levels used in a particular hierarchy is not fixed and should be chosen to reflect the particular problem at hand.

2. The order of the levels should be one that reflects a logical causal relationship between adjacent levels.

3. The number of members in a particular level should be chosen to describe the level in adequate detail.

The points mentioned above indicate that the construction of a particular hierarchy is not a process that follows rigid rules but rather adapts itself to the situation at hand.

Deriving the actual priorities of members in each level is done through a pairwise comparison between each member of the level, relative to a member of the adjacent upper level.

Let us start the technical discussion by demonstrating the derivation of priorities among a set of activities. For illustration purposes, let us consider 3 activities denoted by A_i, $i=1, 2, 3$. We will compare the contribution of these activities to a certain objective. This comparison will be carried out pairwise and the result of the comparison will yield the relative weight, w_i, of the activities under consideration. This pairwise comparison can be summarized in a comparison matrix A given by

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 \\ w_2/w_1 & w_2/w_2 & w_2/w_3 \\ w_3/w_1 & w_3/w_2 & w_3/w3 \end{bmatrix} \qquad \text{(B-1)}$$

The information displayed in this matrix is interpreted as follows: every element, a_{ij}, of the matrix A shows the relative contribution to the objective of the i-th activity compared to the j-th activity, i.e.,

$$a_{ij} \triangleq \frac{w_i}{w_j} \qquad 1 \le i \le n, \quad 1 \le j \le n, \qquad \text{(B-2)}$$

This definition indicates that

$$a_{ij} = \frac{1}{a_{ji}} \qquad \text{(B-3)}$$

which results in the matrix A being a <u>reciprocal</u> matrix; note also that the diagonal of the matrix A in (B-1) is 1's.

Going back, for a moment, to Figure B-1 one can construct a comparison matrix that shows how each of the 3 policies contribute, say, to objective #1. Every element of this matrix can be obtained from this line of questioning:

> "Consider, for example, policy #1 and policy #2; which one contributes more toward objective #1 and what is the strength of this contribution?"

Whenever the ij-th element of the matrix is filled out, the ji-th position is automatically filled out by its reciprocal value.

To actually recover the weights, w_i, themselves rather than their ratios that are given in (B-1) we proceed as follows. Note that

$$Aw = nw \qquad \text{(B-4)}$$

and since (B-1) can be factored out as

$$A = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} [1/w_1 \quad 1/w_2 \ \ldots \ 1/w_n] \triangleq A_1 A_2 \qquad \text{(B-5)}$$

It can be shown (see, e.g., [6]) that the eigenvalues of (B-5) are found from

$$\Pi(A) \triangleq |A-\lambda I_n| = |A_1A_2 - \lambda I_n| = (\lambda^{n-1})|A_2A_1-\lambda| = \lambda^{n-1}(n-\lambda) = 0 \qquad \text{(B-6)}$$

Hence, a comparison matrix as given in (B-1) has (n-1) of its eigenvalues at the origin and the n-th eigenvalue is equal to the dimension of the matrix A, i.e., the number of activities compared (3 in our example).

Since $\lambda=n$ is the largest eigenvalue, we conclude that the vector of priorities, w, is obtained from (B-4) and is simply given as the eigenvector of the matrix A corresponding to the largest eigenvalue $\lambda_{max}=n$. Since we are interested in a relative ordering, this eigenvector is normalized so that its components sum up to one.

There are 3 questions to be asked at this point:

1. How does one quantify his judgement as to the "strength of contribution" of a certain activity?

2. How does one define consistency in this judgement elicitation process?

3. How does one proceed with the process across and beyond a given level?

These questions will be discussed briefly in the remainder of this section.

The comparison process elicits qualitative judgemental statements that indicate the strength of the decision makers preference in the particular comparison made. In order to translate these qualitative statements into numbers to be manipulated to establish the required priorities, a reliable scale has to be established. Much work has been done on the subject of scales in preference statements (see, e.g., references [9], [35] and the references therein), we will not repeat here the arguments that lead to the employment of a particular scale; instead, we will present a scale reported in reference [9] that we find to be useful for our purpose. This scale is shown in table B-1.

Table B-1 Comparison Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

When using this scale, one replaces a qualitative comparison statement with the appropriate quantifier. For example, if policy #1 is weakly preferred to policy #2 as far as achieving objective #1, then $a_{12}=3$ (and by reciprocity $a_{21}=1/3$). Performing the complete pairwise comparison of all 3 policies relative to achieving objective #1 will result in a 3x3 matrix whose (normalized) eigenvector yields the importance of the 3 policies relative to objective #1.

In comparing activities, it is expected that if activity A_1 is preferred to A_2, and A_2 is preferred to A_3 then A_1 should be preferred to A_3. In employing a numerical scale one expects to see consistency maintained throughout the comparison process. Mathematically, consistency is defined as

$$a_{ij} = a_{ik}\, a_{kj} \qquad \forall i,j,k \in \{1,2,\ldots,n\} \tag{B-7}$$

This definition is simple to understand when one recalls (B-2), namely

$$a_{ij} = \frac{w_i}{w_j}$$

then, if one has already established the relative strength of activity i compared to the k-th, and the k-th compared to the j-th activity, then this should also yield the comparison of the i-th to the j-th activity; namely

$$a_{ik}\, a_{kj} \triangleq \frac{w_i}{w_j} \cdot \frac{w_k}{w_j} = \frac{w_i}{w_j} \triangleq a_{ij} \tag{B-8}$$

When the nxn matrix A in (B-1) is consistent its largest eigenvalue is equal to its dimension, i.e., $\lambda_{max}=n$.

When the matrix A is not consistent, i.e., equation (B-7) does not hold for some elements, one can show that the largest eigenvalue of A is always greater than n, i.e.,

$$\lambda_{max} > n \tag{B-9}$$

And the priority vector is obtained by solving the following eigenvector problem for w

$$Aw = \lambda_{max}\, w \tag{B-10}$$

One can define a consistency index by

$$C.I = \frac{\lambda_{max}-n}{n-1} \qquad \text{(B-11)}$$

in the consistent case, C.I = 0. Further details of this subject can be found in [5] and will not be repeated here.

Next we consider how to propagate priorities through the hierarchy. Let i, i=0, 1, 2,...,N denote the i-th level, where i=0 corresponds to the apex of the hierarchy and i=N corresponds to the last (bottom) level. Furthermore, let

$A_j(i)$ - the j-th activity (or attribute) in the i-th level

$P_j(i)$ - the priority associated with activity (attribute) j in the i-th level

$w_{jk}(i)$ - the relative strength of the j-th activity in level i when compared with other activities in the same level, relative to activity k in the (i-1)st level.

Figure B-2 depicts two adjacent levels of the hierarchy, each level with its own number of activites; the actual number of activities in each level is not going to affect the analytical procedure but, only, the number of steps involved.

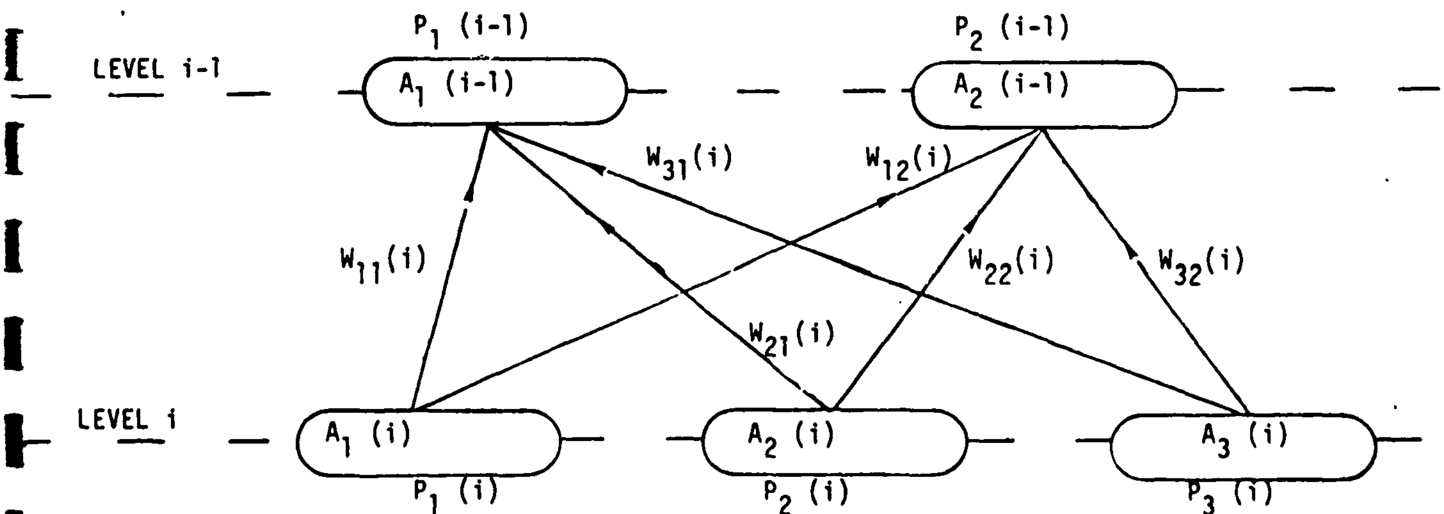

Figure B-2 Adjacent Levels in a Hierarchy

In the situation described in Figure B-2 the priorities in level i-1 have been established, and the next step is to find the priorities associated with the activities of the i-th level. At every level, the priorities are normalized such that

$$\sum_j P_j(i) = 1 \tag{B-12}$$

The relative strength, w_{ij}, of activities in the i-th level are found by constructing a comparison matrix similar to the one described in (B-1), namely

$$\begin{array}{c|c} A_j(i-1) & A_1(i) \;\dots\; A_k(i) \\ \hline A_1(i) & \\ \vdots & A_j \\ A_k(i) & \end{array} \tag{B-13}$$

The matrix A_j in (B-12) is constructed after a pairwise comparison of the activities listed with respect to the activity $A_j(i-1)$, which is the j-th activity in the (upper) adjacent level. Once A_j is obtained, we solve

$$A_j \, w_j = \lambda_{max} \, w_j \tag{B-14}$$

The eigenvector w_j is then normalized so that its components sum up to one.

Remarks

1. The <u>number</u> of A_j matrices to be constructed is equal to the number of activities in the i-1 level, the <u>dimension</u> of these matrices is equal to the number of activities is the i-th level.

2. The arrows indicated in Figure B-2 are drawn to illustrate the direction of comparison.

Once all A_j matrices are constructed and their (normalized) associated

eigenvectors are found, the priorities of the i-th level are found from

$$P(i) = [w_1 \mid w_2 \mid \ldots w_k]\ P(i-1) = W(i)\ P(i-1),\ i=1,2,\ldots,n \qquad \text{(B-15)}$$

where

w(i) is the matrix whose columns are the eigenvectors $\{w_j\}$ and the priority of the apex is

$$P(0) = 1 \qquad \text{(B-16)}$$

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